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Traffic noise mitigation devices and methods

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TRAFFIC NOISE MITIGATION DEVICES AND METHODS

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to the hands of
my darling Wife Neela,
angel Daughter Ninoshi,
my beloved Mother, late Father
and beloved Parents-in-law

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SYNOPSIS

This thesis is related to the exercise of finding more feasible solutions to the intolerable rate of worsening environmental impact caused by road traffic noise. Due to heavy traffic flowing on urban roads, the environmental pollution caused by traffic had become a concern, and the increasing noise levels caused by traffic also needs an urgent attention due to its effects over the general public and their physical and mental well being.

Adverse effects caused by traffic noise are reviewed with respect to designing of more feasible solutions to the problem area. This review highlights community annoyance, health hazards, and the disturbance caused to the general public by the increasing traffic noise levels. Previous findings and the basis for research into further developed methods to mitigate the traffic noise also are emphasised.

Solutions for the worsening traffic noise problem have been sought by application of four strategies, exploring the possibility to improve the; (a) motor vehicle technology; (b) noise barrier technology; (3) road construction technology; and the (4) local area traffic management.

Due to limited period of one year available to complete the study, this thesis paid its prime attention to the development of motor vehicle technology and noise barrier technologies only. The importance of the other two strategies is also pointed out.

Number of surveys and tests related to road traffic noise were conducted, and some more relevant data has been accessed though the local authorities. Assessment of the previous research carried out by the Society of Automotive Engineers (SAE) of the United states of America, and some other researchers are also carried out. Some modifications also were suggested in the areas such as the noise reduction methods for vehicle engines, exhaust systems, tyres, body work and suspension, use of thick tree shrubs as natural and economical noise barriers, and the use of clay bricks as more successful noise absorption type building material etc.

A new traffic noise prediction model was developed by the author as a result of this research, to suit with the Australian traffic Environment as presented in this thesis. Some fruitful proposals also were presented to be sucessfully used as devices and methods, in an economically beneficial, and environmentally friendly way to mitigate the traffic noise.

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A	"A" Weighting Function	11
AC	Alternative Current	142
ACSVD	Advisory Committee for Safety in Vehicle Design	55
ADR	Australian Design Rule	55
AEC	Australian Environmental Committee	55
AM	Before Noon (Anti meridian)	43
AM-5000	Type of an Ameo Meter (Air Velocity Measuring Instrument)	68
AMVCB	Australian Motor Vehicle Certification Board	51
Anon	Anonymous	94,101
ARRB	Australian Road Research Board	14, 52
AS	Australian Standards	11, 19, 48, 49, 52, 56, 58, 119
ATAC	Australian Transport Advisory Council	51
B & K	Bruel and Kjaer - Acoustic Instrument Manufacturer	68, 70, 102, 105, 106, 117, 118, 119, 123
BS	British Standard	24
C	Passenger Cars	117, 118
CC	Cubic Centimetres	77
Choseb	A community living in Austria	13
C^0	Celsius measurement of Temperature	75
CORTN	Calculation of Road Traffic Noise Model	15, 17, 60, 70, 71
CBD	Central Business District	52
cm	Length measured in Centimetres	99, 52
dB	Noise Level in Decibels	9, 19, 21, 31, 38, 42, 44, 45, 47, 49, 50, 58, 67
dB(A)	Noise Level With "A" Weighting	22, 23, 24, 27, 32, 33, 42, 49, 52 55, 57, 58, 59, 60, 61, 65, 66, 67, 68, 69, 71, 77, 80, 84, 85, 86, 87, 90, 99, 100, 101, 104, 106, 111, 112, 13, 114, 115, 116, 119, 121, 127, 128, 129, 131, 132, 133, 134, 135, 136, 139
DoE	Department of Environment -United Kingdom.	11, 12, 15, 17, 26, 56, 60, 63, 71, 73
DNL	Drive - by Noise Level	109, 105, 110, 111, 112, 113, 114, 115, 118
EEC	European Economic Community	56
EPA	Environment Protection Authority	55
F 6	F 6 Freeway	70, 104, 141
FL 1011	The Model Number of a Vehicle Engine	94
FM	Frequency Modulated	102, 142

GVW	Gross vehicle Weight	24
HGV	Heavy Goods Vehicle	23, 26, 55, 61,71, 139
HGV(B)	Heavy Goods Vehicle Category (Bus)	117, 118, 119
HGV(MC)	Heavy Goods vehicle Category (Motor Cycle)	117, 118, 119
HGV(R)	Heavy Goods Vehicle Category (Heavy Rigid Truck)	117, 118, 119
HGV(T)	Heavy Goods Vehicle Category (Trailer - Articulated Semi Trailer, Draw Bar Trailer, Drawn Either by a Rigid or Articulated Tractor	117, 118, 119
% H.V.	Percentage of Heavy Vehicles	109, 139
Hz	Frequency in Hertz	28, 29, 35, 36, 37, 43, 47, 48, 50, 57, 58, 129
ISO	International Standards Organization	43
kg	Weight in Kilograms	65, 123
kg/m^2	Mass in Kilograms per Metre Squared	62
kg/m^3	Density in Kilograms per Metre Cube	39
kHz	Frequency in Kilohertz	28, 29, 40, 47, 55
km/h	Speed in Kilometres per Hour	27, 29, 31, 71,77,80, 104, 106, 127, 128, 131, 132, 133, 134, 135, 139
kN	Force in Kilo Newtons	65
KUSTOM	KR 11 Model and Type of Radar Speed Measurement Equipment	75
L_{10}	Noise Level Exceeding 10% of the Time	3, 16, 17, 20, 49, 68
L_{10} (1h)	Noise Level Exceeding 10% of One Hour Period	9, 10, 11,12
L_{10} (3h)	Noise Level Exceeding 10% of Three Hour Period	43
L_{10} (18h)	Noise Level Exceeding 10% of Eighteen Hours Period	9, 10, 12, 43
L_{10} (24h)	Noise Level Exceeding 10% of Twenty Four Hour Period	11
$L_{10} + 5$	Noise level Exceeding 10% of Time and the contribution due to Excess Truck Noise	20
Leq	Equivalent Continuous Sound Level	68
L_{np}	Noise Pollution Level	43
LT	Light Trucks - Small Rigid Trucks Including Pick-ups, Panel Vans and Small Buses Mounted on a Chassis (Rear Single Wheel)	117, 118, 119
LPG	Liquid Petroleum Gas	53
λ	Wave Length - Lambda	36
m	Length in Meters	72, 77, 78, 79, 80, 106
Mack	Mack Brand Heavy Vehicles	77
MAN	MAN Brand Heavy Vehicles Manufactured in Germany	94
Mg	Weight in Megagrams (Tons)	31, 77, 78
mm	Length in Millimetres	28, 31, 79, 80

m/sec	Meters per Second	35
MT	Medium Trucks - Medium Size Rigid Trucks Mounted on Single Chassis With rear double Wheels	117
MTG	Motor Transport Group	52
mW	Energy in Milliwatts	47
μW	Energy in Microwatts	47
μpa	Pressure in Micro Pascals	36, 40
NAASRA	National Association of State Road Authorities - Australia	3, 14, 106
NC	Noise Criterion	44, 55
NCHRP	National Co-operative Highway Research Project (USA)	17, 60
Nm	Power in Newton Metre	46, 101
N / m^2	Young's Modulus in Newtons per Metre Squared	42, 44
NTC - 350	A Model of Cummins Engine Series	93
NS/m^3	Impedance in Newton Seconds per Metre Cube	42
NR	Noise Rating	47, 55
OECD	Organization for Economic Co-operation and Development-Paris	14
PSI	Pressure in Pounds per Square Inch	123
RPM	Rounds per Minute	119, 121
RMS	Root Mean Square Value of Pressure Fluctuations	36
RTA	Roads and Traffic Authority	51
SAE	Society of Automotive Engineers (United States of America)	19
SIL	Speech Interference Level	50, 51
SPL	Sound Pressure Level	36, 47
SRA	State Roads Authority	9
Streeter Amet	Automated Computerised Traffic Counter	102, 106
TL	Transmission Loss	64, 65, 66, 67
TRRL	Transport and Road research Laboratory (United Kingdom)	23, 24 27, 30, 31, 32, 33
TV	Television	3
UK	United Kingdom	1, 11, 13, 14, 17, 20, 22, 24, 30, 49, 51,52, 56, 60, 63, 72
USA	United states of America	1, 11, 13, 17, 20
USEPA	United States Environmental Pollution Authority	49, 56
veh/h	Vehicles per Hour	71, 74, 106
veh/day	Vehicles per Day	55
VENSAC	Vehicle Emissions Noise Standards Advisory Committee	56, 57
W	Energy in Watts per Metre squared	42
ZF-8S 180	Type of a Gear Box Model for Heavy Vehicles	101

LIST OF NOTATIONS

Notation	Description	Page
d_s	Line of Sight Distance from source to Receiver in Meters	16
d	Distance Along the Ground from the Traffic Lane to an Observer at a Check Point	16
d	Distance Between Near Side Traffic Lane and the Observer	21
P	Percentage of Heavy Vehicles	20, 21
P	Probability of ith Measurement Interval	14
P	Atmospheric Pressure	40
P_0	Atmospheric Pressure	41
p	Coarseness of Road Surface	16
Q	Number of Vehicles Counted During 0600 to 2400 Hours	5
Q	Total Hourly Flow of Vehicles	20, 21
q	Number of vehicles Counted During one Hour	15
V	Average Speed of Vehicles	20, 21
V	Speed of Sound	38
V	Volume of Air	40
V	Total Volume Created	41
δV	Amount of Volume Increased	40
v	Speed of a vehicle	15

CHAPTER 1

THE ENVIRONMENTAL IMPACT OF TRAFFIC NOISE

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THE ENVIRONMENTAL IMPACT OF TRAFFIC NOISE

1.1 INTRODUCTION

The environmental impact of road traffic is a complex problem involving many factors, attracting considerable public concern. Although mankind has been subjected to many different sources of sound throughout history, it is only during recent years that sound has significantly affected mankind adversely as noise, which can be described as undesirable, unwanted sound. It has grown to alarming proportions as a result of the development of industry, the urbanisation of the society, and developments in air and road transport.

Surveys conducted by the State Pollution Control Commission in Sydney, and other concerned authorities in the UK, USA, and Europe have identified traffic noise as a major source of environmental noise in urban areas. The loudest and most annoying traffic noise is caused by trucks, motor cycles and cars with defective silencers, mufflers or modified exhaust systems. In the Sydney metropolitan area alone, unacceptable traffic noise affects about two and half million people. The number of people suffering from this will increase drastically unless urgent measures are taken to mitigate the traffic noise. The most effective methods of reducing this noise can be obtained by developing devices for control of the noise emissions from all motor vehicles, especially from trucks, utilising the motor vehicle technology, and by developing sound barrier technology. However other aspects such as road construction technology and local area traffic management will also be a mean of overcoming or reducing road traffic noise.

The State of New South Wales has undergone a considerable industrial and economic development during the past few decades, and although the road network has contributed significantly to this development in number of ways, the heavy traffic flow that gradually developed on the urban roads has become a threat to the environment of most regions. Due to the intolerable worsening of the environmental impact caused by traffic, the authorities concerned have to seek more technically and economically feasible solutions to control the situation. Many research programmes were carried out and the results were adapted to real world situations in an attempt to control the impact of traffic noise.

1.2 ENVIRONMENTAL IMPACT CAUSED BY TRAFFIC

The impact of traffic is a vast subject, particularly when the damages caused to the biological and physical environment by motor vehicles and the road network associated with it is considered. It can be clearly seen that the following threats are faced by the environment of urban New South Wales due to the growth of heavy traffic. Following damages to the living environment are caused due to the presence of traffic.

1. Noise pollution
2. Air pollution
3. Loss of living amenities
4. Community disruption
5. Destruction of agricultural land and crop production
6. Deterioration of rural scenic landscape
7. Disturbance of places of recreational interest
8. Contamination of water in lakes and low lands due to rain water washing off of the acidic, alkaline and other, harmful compounds from the road surfaces
9. Destruction of places of cultural heritage
10. Destruction of the rain forests
11. Loss of valuable species of native animals and birds
12. Loss of valuable species of native trees due to land clearance
13. Adverse effects on residential access and amenity
14. Pedestrian hazards due to insufficient crossing facilities and other access.

An analysis of the above factors using the factor weighting technique indicates that noise pollution caused by traffic produces a very severe environmental impact that requires urgent attention (RTA, 1990)

1.3 NOISE

Noise is an unwanted sound producing an adverse response in the hearer. In an objective sense, the noise is usually found to contain either many inharmonious components or excessive amplitudes (Bryant, 1975).

1.3.1 Traffic Noise

Some people like noise, but some people don't. Social surveys carried out by the Environmental Authorities of USA, UK and here in New South Wales, have identified road traffic noise as one of the most important factors causing unwanted environmental effects in urban areas.

At low traffic speeds, such as those encountered on urban roads, the majority of the vehicle noise is radiated by individual vehicles resulting from the interaction of several sources such as the engine, exhaust system, transmission system, brakes, body and suspension noise, and the tyre and road interaction. Minor noises are caused by factors including intake air and cooling system fan.

Traffic noise results from the summation of the noise radiated by individual vehicles. Stop start conditions due to congestion and traffic signals, and accompanying vehicle acceleration, do cause noise increases. Gear changes required for climbing steep inclines also contribute to the problem. The traffic noise is transmitted to the hearer through the air and therefore depends upon the temperature, pressure, and humidity of the air. The traffic flow and speed, the condition and the type of road surface, grade and tyre / road interaction all play a considerable role in the generation of unwanted sound. As the speed rises, the noise attributable to the tyre-road interaction and to air disturbance also increases (NAASRA, 1974).

1.3.2 Adverse Effects of Traffic Noise

Traffic is the major factor which contributes to the movement of goods and people from one place to another and existence of human life depends on traffic and transportation. But, there are a large number of adverse effects caused due to traffic noise. The adverse effects caused by traffic are given below:

Significant lowering of property values, home rent, and home marketability's
Physical health
Psychological annoyance
Nervous stress
Lower hearing ability
Can cause the total deafness
Disturbance to sleep
Interference to speech and conversation
Disturbance of the enjoyment of radio and TV programs
Causes accidents
Diminish the accuracy of work
Lowering the productivity at work places
Aggravate heart diseases
Causes the undue stress on teachers and the students in the schools and sportsmen of the play grounds located near main roads.

1.4 AIMS AND OBJECTIVES OF THE RESEARCH

The primary aim of this research is to predict an acoustically efficient and cost effective technology to minimise traffic noise levels.

The secondary objective of this thesis involved the following methods for achieving the primary objectives.

- Appraisal of the existing level of impact due to the traffic noise problem.
- Appraisal of the existing devices for measuring noise levels
- Appraisal of the existing technologies aimed at curbing noise levels.
- To find cost effective noise reduction technologies, so that the burden of cost to the road user may be minimised.

1.5 RESEARCH APPROACH

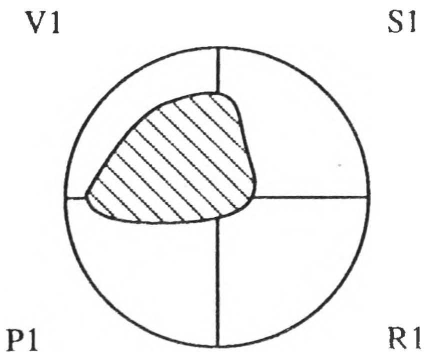
An integrated approach was used to predict the traffic noise reduction devices, as the noise is an outcome of many factors. These factors will include,

(a) Available vehicle technology
(b) Available sound barrier technology
(c) Available road construction technology
(d) Planning and rerouting of traffic in and around urban areas.

An economically optimum technology under varying environmental, traffic and other conditions such as varying levels of vehicle, road construction, and sound barrier technologies and traffic planning was found.

The illustration of the method developed is given below:

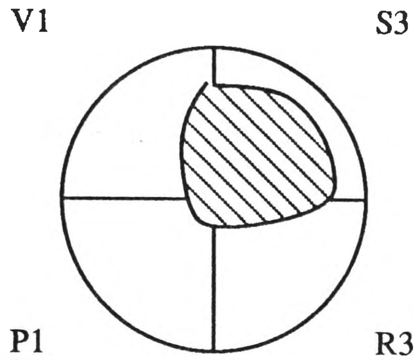
1.5.1 Assuming 3 Vehicle Technologies (The variable is 'V').



V1 = Using block tread tyres
V2 = Encapsulation of engine and transmission.

V3 = Improved silencers.

1.5.2 Assuming 3 sound barrier technologies (The variable is 'S')

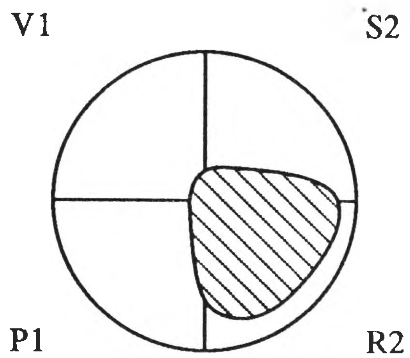


S1 = Sound barrier mounds

S2 = Parapet walls

S3 = Tree planting

1.5.3 Assuming 3 Road Construction Technologies (The variable is 'R')



R1 = Using open graded asphalt

R2 = Depressing the arterial road

R3 = Elevating the arterial road

1.5.4 Assuming Local Area Traffic Planning Methods (The variable is 'P')

P1 = Re-routing the heavy traffic away from urban areas

P2 = Adherence to stringent traffic noise regulations

P3 = Enforcement of specific speed control limits

Figure 1.1 The best (optimum) Solution under each permutation.

Accordingly there were several possible combinations or Permutations. it was worked out as shown in Figure 1.2. There were 27x3 combinations, and out of them 3 combinations were illustrated here for reference.

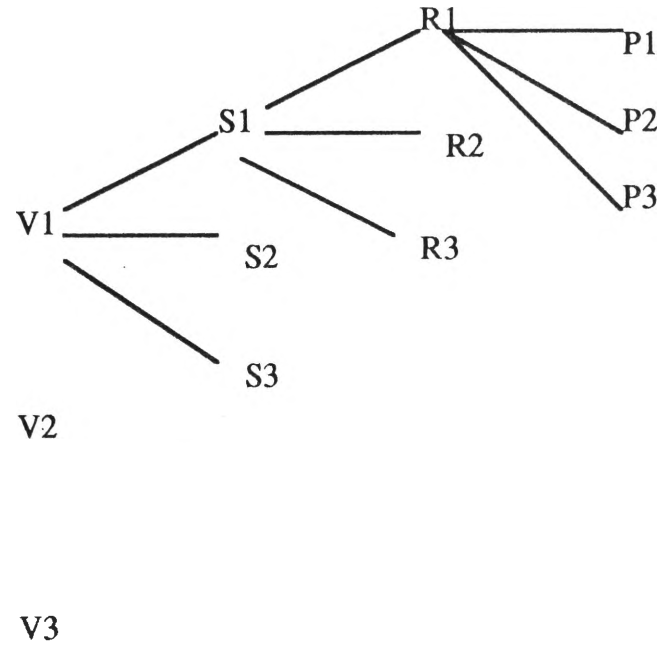


Figure 1.2 27X3 = 81 combinations

Results of the above combination under varying conditions are obtained by multiplying the number of experiments done. As the influence under 2 conditions have to be found, the number of experiments have become=27x3x2= 162. The optimum solution under each permutations is shown under each panel of Figure 1.1.

The traffic noise mitigation exercise is a vast field, which needs extensive and expensive research work throughout a long period. Due to the above fact, within the available limited duration and the resources, this research has paid attention only to the first two starategies namely, motor vehicle technology and the noise barrier technology, out of the four strategies mentioned in the research approach. The research approach for studying the objectives set out above was based on the following directives:

- By measuring the traffic noise levels in relation to the different traffic flows, vehicle mixes, barrier protection of the earth mounds and embankments, depressed or elevated road ways, sound barriers made of wood, clay or concrete type wall bricks, corrugated Aluminium sheets, natural vegetation, artificially planted thick tree bushes, and predicting the effect of them in traffic noise mitigation exercise.

- By measuring the transmission through different types of building materials such as plaster board, clay bricks, concrete bricks, masonry plastered walls, clay roof tiles, corrugated galvanised roof sheets, asbestos roof sheets, asbestos ceiling sheets, wooden ceiling sheets, carpeting etc., and to predict their effectiveness as traffic noise mitigation devices.

- By measuring, the noise levels generated by different units of heavy vehicles, such as engine, transmission, exhaust, tyres, suspension, quick release levers of the trailers, body etc., and to predict more improved methods to mitigate the noise generated by those units.

- By utilising the above data collected, developing a new traffic noise prediction model to match with the existing Australian traffic conditions.

1.6 RESEARCH PROGRAMME

This thesis is concerned with the study of prevailing traffic noise levels within the Illawarra Region of New South Wales, Australia, in relation to the factors such as traffic flow, vehicle mix, speed, individual vehicle noise, pavement texture, road profile, distance from source to the receiver, nature of the ground, angle of view of the traffic stream, screening effects, relationship to the weather conditions, effects of noise barriers, and the noise levels generated from heavy vehicles under freely flowing traffic conditions to find solutions to the traffic noise problem.

The technique used for the accomplishment of the research is based on interrelated strategies shown in the schematic diagram of Figure 1.3.

Chapter 2 contains a review of relevant research work carried out concerning the traffic noise mitigation exercise to identify the problem areas and outline the methods of traffic noise mitigation. "Environmental impacts due to traffic", have been pointed out with special emphasis to the traffic noise impact. Importance of the traffic noise measurement is clarified, and several methods and models and their application are discussed. Eventhough, the methods for traffic noise mitigation by developing the devices such as noise barrier technology, road construction technology, and local area traffic management are discussed, the value of the reduction of noise at source is emphasised.

Chapter 3 contains the basics regarding the sound wave and it's characteristics, acoustic theory related to the traffic noise, community annoyance levels, noise control regulations and standards, sound transmission in air, and traffic noise reduction device such as noise reduction at engine and transmission, exhaust and intake, tyre, body, suspension, and their benefits. The major emphasis of the chapter 3 was given to the effectiveness tests of the sound barriers studied by the author of this thesis at a number of sites in Wollongong area. Instrumentation, the results from the site surveys, and predicted developments of the research also have been presented.

Chapter 4 had been devoted to the field experiments done related to developments in motor vehicle technology. Their results have been presented, and predictions based on them for traffic noise mitigation exercise. Most of the field work had to be confined to Wollongong city council area due to limited period of one year, and limited resources available for this research. Field experiments were carried out using the vehicles of the technical staff and the departmental vehicle of the Civil and Mining Engineering Department of the University of Wollongong.

Chapter 5 includes the discussion of the findings and the proposals to mitigate the traffic noise, at environmentally friendly, economical, user friendly atmosphere, utilising sound barrier technology, and the motor vehicle technology. Further suggestions have been made, related to further reduction of traffic noise by utilising the road construction technology and local area traffic management. Importance of further research funded by the concerned authorities also was emphasized.

Figure 1.4 shows the "Project" Duration Bar Chart" which clarifies the time spent by the author of this research.

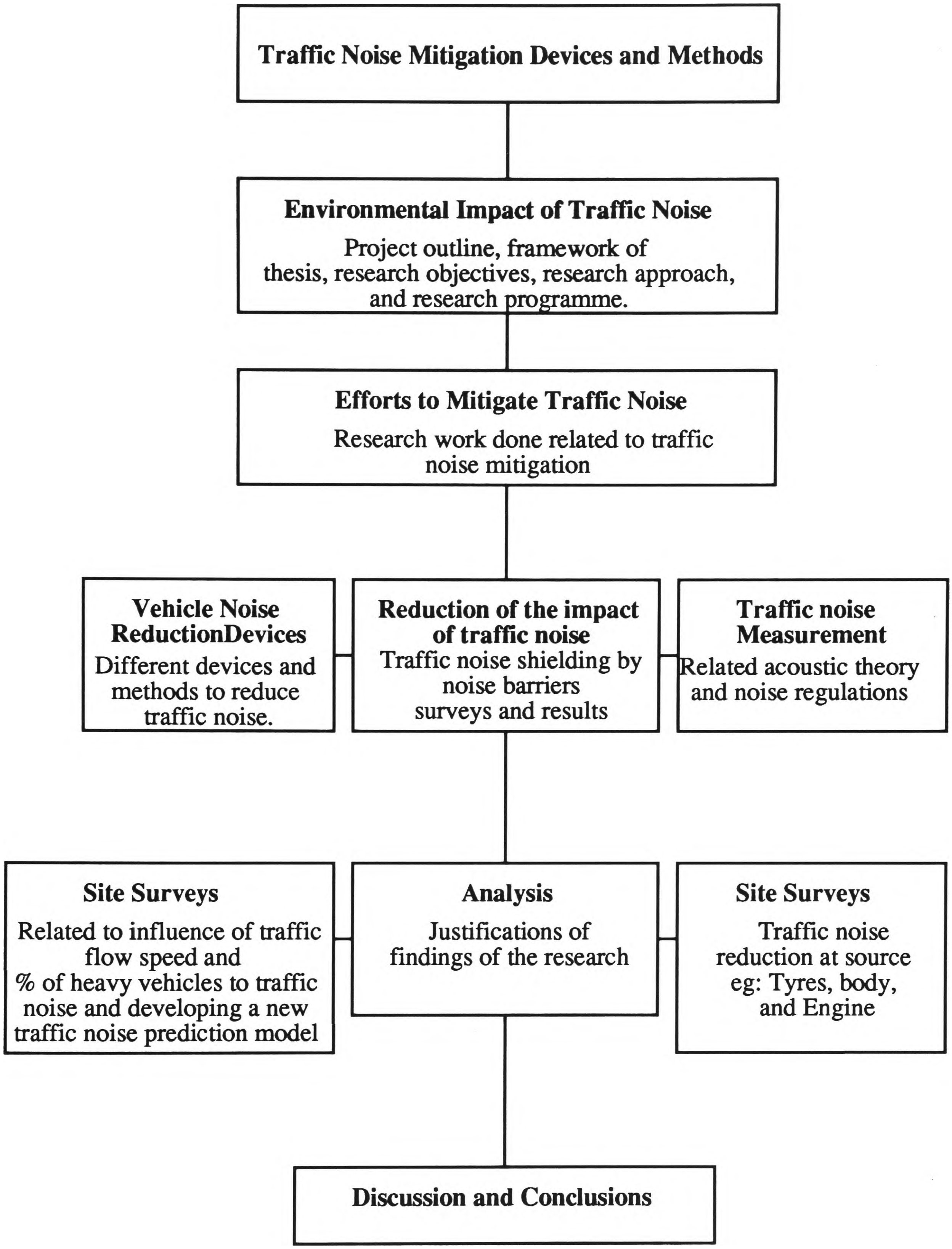


Figure 1.3 Schematic diagram of thesis program

The research was conducted according to the schedule given in figure 1.4 as a project duration bar chart

THESIS PROJECT DURATIONS

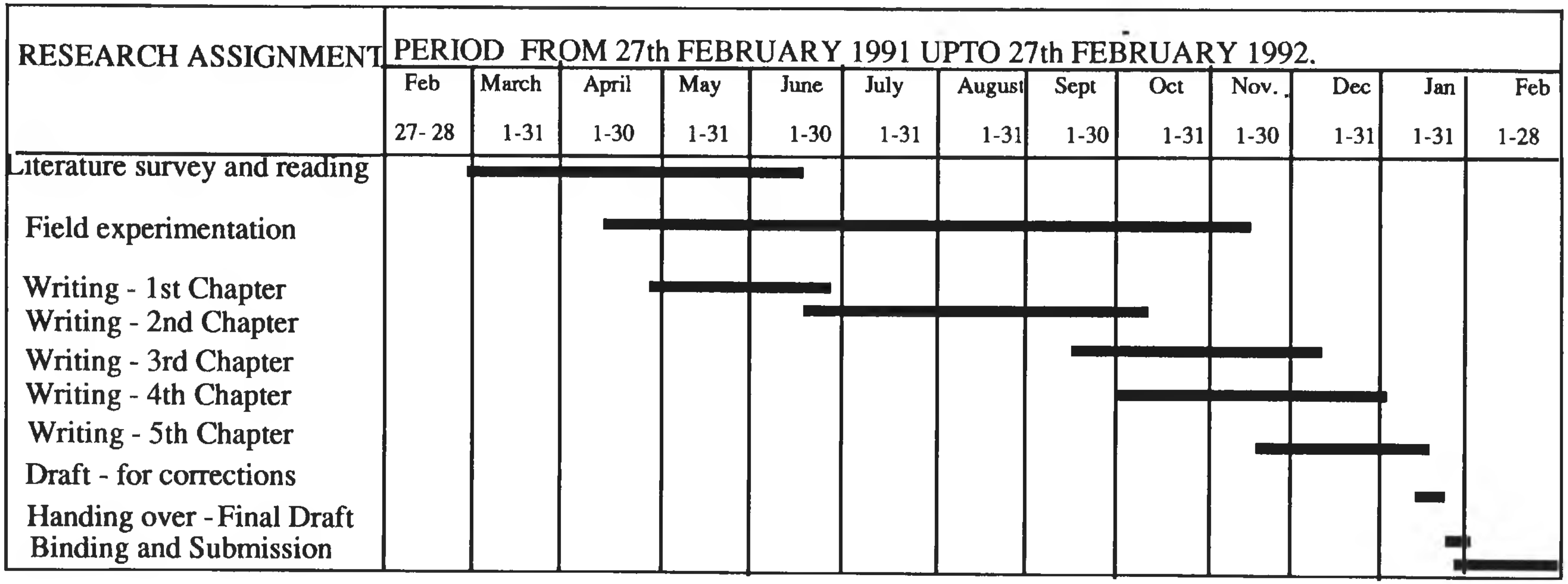


Figure 1.4 Project Duration Bar Chart

CHAPTER 2

MITIGATION OF TRAFFIC NOISE

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MITIGATION OF TRAFFIC NOISE

2.1 INTRODUCTION

The noise environment in a typical house is such that it is possible to talk at any time, to sleep or work, listen to radio and TV without disturbance from excessive noise. In that context, the degree that the traffic noise's tolerated by a house holder depends on his occupation, socio - economic status, and the general neighbourhood reaction

Research work has been carried out in the UK, USA, and in Australia as well, in areas such as the sources of traffic noise, traffic noise measurement, and traffic noise mitigation. Some models had also been developed as part of the research, e.g. Brown (1978).

In this chapter details of such surveys research and models, obtained from the relevant literature are presented. This chapter includes the findings resulting from those surveys and their applicability. An attempt has also been made to see that the best of the above models could be adapted to the existing traffic environment in New South Wales, Australia, aimed at mitigation of existing traffic noise levels. Previous research work on "Quieter Vehicle" also has been emphasised.

2.2 TRAFFIC NOISE RELATED RESEARCH

The method of assessing residential area traffic noise is contained in the Australian Standard AS 1055 - 1978. It is based on comparison of the measured noise level with an appropriate 'acceptable' background level determined from experience or measurements in the absence of annoying noise. The comparison levels can be used as a guide in establishing acceptable noise levels or for estimating the validity of noise complaints. Following AS 1055 - 1978, the measured noise level is first adjusted to take into account the other relevant characteristics of the noise, such as impulsiveness and tonal qualities. An adjustment is made to the measured values if the noise:

- o is impulsive: e.g. hammering bangs, thumps at a rate of less than 10 per second.
- o have prominent tonal components: e.g. whines, screeches or hums.
- o has beats or amplitudes or frequency modulation.

These noise levels are defined as average maximum values "determined over a sufficiently long time which represents the annoying effect" (using "A" weighting), This

This approach would be used if for instance low frequency sounds predominate.

Figure 2.1 clearly shows that one of the first indicators of early noise annoyance level occurs when visitors to a house comment on the noise.

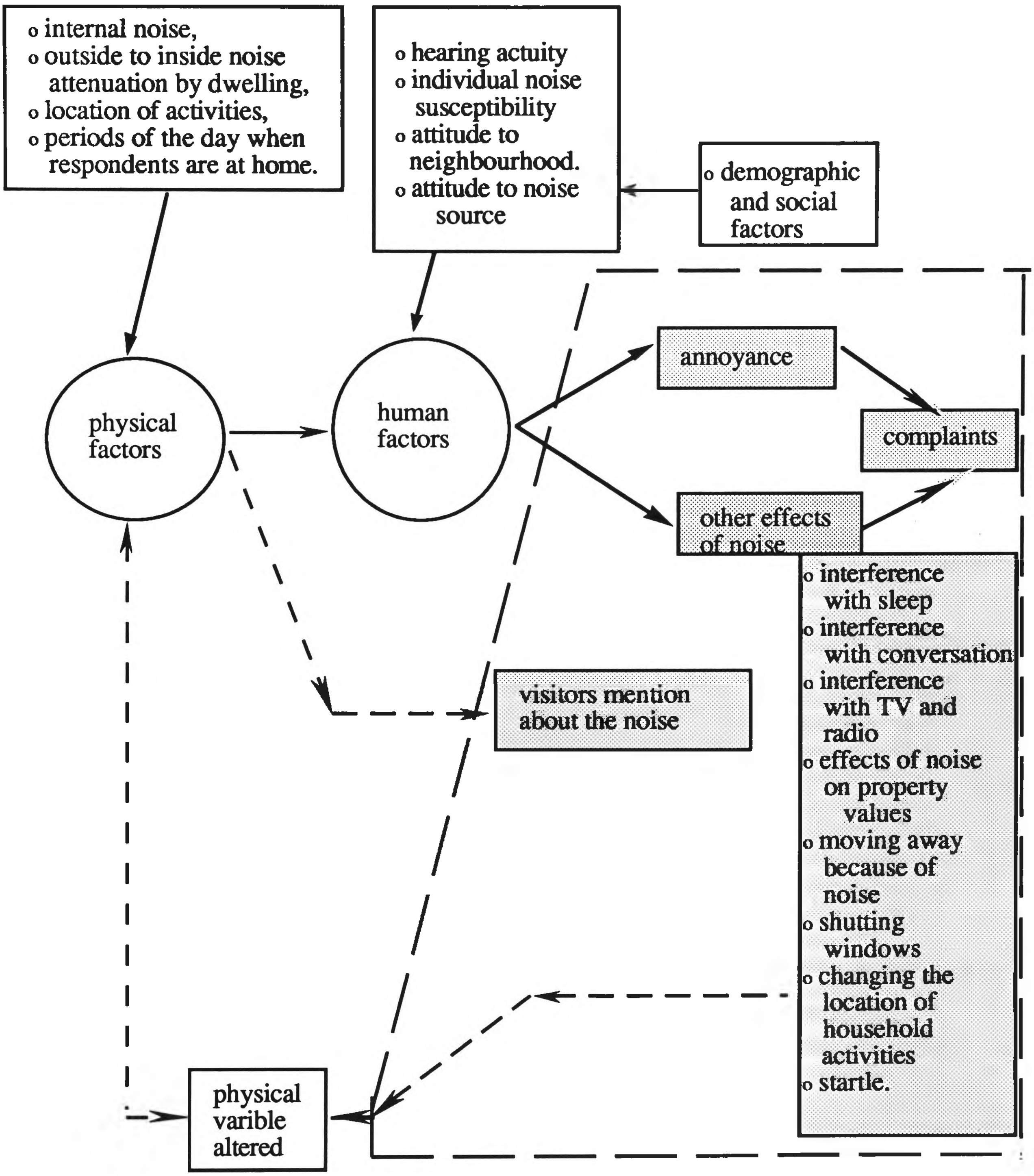

Figure 2.1 Conceptual model of relationship between road traffic noise and it's effects on people in their homes (Brown, 1980).

The acceptable maximum noise levels out of doors in residential sites ranges from 35 to 70 dB(A) in the early hours of morning for low density transportation sites during weekdays.

The annoyance that people feel when they are exposed to traffic noise would be expected to be related to the average sound levels and to the frequent peaks aggravating the situation. Certain sound frequencies such as low frequency truck noise can be particularly annoying. Annoyance is also influenced by perception of the hearer who may think that the noise is reasonable and unavoidable and it is also related to its influence on property value (NAASRA, 1974). Due to the complexity of the noise annoyance, local researchers are still trying to determine the relationship between noise annoyance and sound levels. Overseas studies such as Saunders and Jameson (1978) and Brown (1980), have shown some links. Brown was able to find that annoyance would not be recorded if L_{10}(18h) values were below 60 dB(A) or L_{10}(1h) is below 65 dB(A). The various studies show that an individual's responses begin to be affected by noise, when it is about 60 dB(A) and above. Researchers are still a long way from understanding the relationship between the noise as it is measured and the noise as people subjectively hear. Solutions have to be found to close this gap, and more stringent noise legislation is required until suitable solutions can be found.

Brown (1980) noted in a review of overseas requirements that the acceptable acoustic standard in the UK - L_{10}(18h) is 68 dB(A), while in the USA the - L_{10}(1h) is 60 dB(A) to be perceived for serenity and quiet. The UK levels have been adapted by some Australian State Road Authorities (SRA) (Stone and Saunders, 1982). In calculating this effect from traffic noise models, it is usual to predict traffic flow levels for the next ten years.

The vehicle noise emissions studies are still desperately short on facts, (Transport Engineer, 1990). A disturbing finding by Moser (1990) showed that, certain noise combinations seemed to cause damage to the pituitary gland, the cardio vascular system, the renal systems and the sexual organs, and other parts of the human body. Although, he has not explained the mechanism by which such damage is caused, it demonstrated that noise could cause such damage in a high percentage of people, particularly the younger and older extremes of the age spectrum.

Tenuous support came from the results of research by the Austrian District Health Authority, which had conducted long term surveys on Choseb (a local rural community of Austria) communities. One such community, straddling a main arterial road, had featured a cardio vascular and nervous system problem in 49% of all deaths in 1979-1980 period. When the township was by-passed in the 1985-86 period, cardio vascular problems and nervous system factors affecting the total deaths recorded had fallen to 24%. This indicates that traffic noise has a severe effect on the well being of the people.

2.2.1 Prediction of Road Traffic Noise.

The noise from road traffic affects urban areas and even suburban and rural areas. Although the sound produced by individual road vehicles is not great as that produced by individual air craft, the combined effect is significant. Moreover, the total number of road vehicles is increasing as is the proportion of the population living close to the source of noise. One example of this is the frequent replacement of single family houses by multi family dwellings adjacent to main roads.

As mentioned before, the relationship between objective measurement of road traffic noise and the subjective annoyance caused by the noise is very complex. The effects of noise on a particular activity, such as speech communication can be measured under laboratory conditions.

L_{10} is the most common unit used for expression of noise from road traffic assessed over an 18 hour period [L_{10} (18h)] between 0600 to 2400 hours, which is the level exceeded for 10% of the time. Sometimes a one hour L_{10} period [L_{10} (1h)] is used. Some authorities prefer to use L_{10} 24 hour level [L_{10} (24h)], and this correlates strongly with L_{10}(18h), (Hothershall and Salter, 1977). Some authorities prefer to use the equivalent energy level (L_{eq}). The L_{eq} is the energy mean of the noise sample and it is calculated by using the following formula.

$$L_{eq} = 10 \log_{10} [\sum_{i=1}^{n} P_i \, 10^{L_i/10}] \qquad (2.1)$$

where

P_i = Probability of noise level lying in 'i'th measurement interval

L = Mid point of the above measurement interval

Recent investigations (UK DoE 1975, NAASRA 1974) have revealed that L_{eq} and L_{10} correlate highly with noise levels known to cause community annoyance. Burgess (1977) suggested that:

$$L_{10} = L_{eq} + 3 \qquad (2.2)$$

Noise Level prediction models have been developed overseas and in Australia. The model, "Predictions of noise levels from freely flowing road traffic", (Brown, 1978) can be taken as one of the examples. Most of those models have considered only Free-Flow Traffic conditions. Brown (1980) as a part of an Australian Road Research Board (ARRB) sponsored noise prediction project, had examined the performance of several models in predicting noise levels at a housing facade along 19 roadways carrying freely flowing traffic in Brisbane, Sydney and Melbourne areas. The results were compared to levels measured at the sites. Brown had recommended that the Department of Environment (DoE) model would be the best for predictions of road traffic noise in urban areas in Australia.

2.3 DEPARTMENT OF ENVIRONMENT MODEL

A detailed explanation of this model has been named as "Calculation of Road Traffic Noise" (CORTN) given in the publication of the Department of Environment of UK DoE (1975), and (Brown, 1980). The $L_{10}(18h)$ index has been adopted by the British government for planning, and to determine entitlement of dwellings to sound insulation treatment. The DoE method for predicting $L_{10}(1h)$ and $L_{10}(18h)$ noise levels due to road traffic at points up to 300 meters from the road, which is carried out in series of steps, each involving the use of the formula is also presented graphically. In many situations, charts were used to obtain accuracy, but in cases where a high accuracy such as better than 1dB(A) was required the calculations were based on definitive formulae given.

The following formulae are used to estimate the noise values at kerbside based on either $L_{10}(18h)$ or $L_{10}(1h)$ parameters;

$$\left.\begin{aligned} L_{10}(18h) &= 28.1 + 10 \log_{10} Q \\ L_{10}(1h) &= 41.2 + 10 \log_{10} q \end{aligned}\right\} \qquad (2.3)$$

Where

Q = No of vehicles during a traffic count between 0600-2400 hours.
q = No of vehicles during a one hour traffic count.

It has been assumed that the average speed is 75 km / hour, and there are no heavy vehicles on the road.

The correction factor (C_1) for the variation of the speed (v) is given as:

$$C_1 = 33 \log_{10}(v + 40 + 50 / v) + 10 \log_{10}(1 + 5p / v) - 68.8 \qquad (2.4)$$

The correction factor (C_2) given for road gradient (for climbing traffic) is:

$$C_2 = 0.3\ G \tag{2.5}$$

Where

G = Percentage of the gradient.

The correction factor (C_3) given for coarse texture road surface is:

$$C_3 = 4 - 0.03P \tag{2.6}$$

Where

p = coarseness of road surface. (Unit of measurement is based on the type of road construction material used in the country).

The correction factor (C_4) given for distance, road and the nature of the ground when more than 50% of the surface is non absorbent such as bitumen concrete or water for absorbent-grassland the correction is shown in equation 2.7.

$$C_4 = -10 \log_{10}(d_s / 13.5) \tag{2.7}$$

where

d_s = Line of site distance from the source to the receiver in meters.

When more than 50% of the surface is absorbent such as grass, then the correction is:

$$C4 \begin{cases} -10 \log_{10}(d_s/13.5) + 5.2 \log 10[3h/(d + 3.5)] \text{ for } 1 < h < (d + 3.5)/3 \\ -10 \log_{10} (d_s/13.5) \text{ where } h > (d + 3.5)/3 \end{cases} \tag{2.8}$$

Where

h = Height of the check point above the ground. (in meters)

d = Distance along the ground from the traffic lane to the observer at the check point. (in meters)

Accordingly, the final estimate of traffic noise on a given roadway can be made by summation of the corrections (C_i values) .

$$L_{10} = L_{10} + \sum_{i=1}^{n} C_i \tag{2.9}$$

The aggregate noise levels at a given location with more than one road can be obtained using logarithmic addition of the individual noise levels. When there are two noise levels E.g. L_1 and L_2 dB(A), where $L_1 > L_2$, the value of L is given by the following formulae.

$$L = L_1 + 10 \log_{10} [1 + 10^{(L_2 - L_1)/10}] \tag{2.10}$$

Even though basically, the CORTN model is meant for open country, further modifications are possible as outlined in UK (DoE, 1975). The National Cooperative Highway Research Program (NCHRP) method developed in the USA, (Gorden et al., 1971) also is a well known traffic noise prediction model. Hothershall and Salter (1977) provided a comparison between the NCHPR method and the CORTN method. Stone and Saunders (1982) studied the traffic noise levels in Australian roads, and mentioned that the CORTN model requires a further correction of -0.7 dB(A) to allow its application to the traffic conditions on Australian roads. Samuels (1986) claims that the CORTN method is more accurate and has less variability than the NCHRP method.

The CORTN model is based on two types of vehicles (cars and trucks). The improved accuracy for the CORTN model may be achieved by using three vehicle groups such as cars, car based vans of 3000 kg unladen weight; greater than 3000 kg and trucks with 3 or more axles (Nelson. P, 1973) The input data for the above three vehicle types were not available in the ARRB study.

The CORTN model also assumes a certain mix of trucks; from two axles with four wheels upto, say, six axles with twenty two wheels, the vehicles all having different acoustic emission intensity and characteristics. CORTN model has been found to predict noise levels insufficiently, when the truck traffic contains many heavy trucks (DoE, 1975).

Since the empirical and theoretical traffic noise prediction models have tended to control or ignore certain variables, many models are limited to fixed propagation models developed by the regression of measured traffic conditions and distance on measured noise levels. Data such as road way factors etc., were generally controlled or ignored.

Hence, the development of procedures for the prediction of noise levels under more complex situations for the prediction of the effect of the vehicle noise reduction devices represents the main thrust of this thesis. This is achieved by combining various empirical, theoretical, and simulation data including the effects of propagation variables as well as source variables. These source and propagation variables are listed below.

Source Variables

1. Number of vehicles on the road (Traffic flow)

2. Vehicle characteristics
   (a) Acoustic emission strength of individual vehicles
   (b) Vehicle speed
   (c) Vehicle types and condition
   (d) Vehicle load
   (e) Tyre type and tread design

3. Road way factors
   (a) Road way grade
   (b) Road way surface
   (c) Road way condition due to weather (wet or dry)

4. Driving conditions
   (a) Free flow
   (b) Stop start condition (Acceleration) Etc.

Propagation Variables

1. Distance
2. Ground cover
3. Height of source of noise emission from vehicles
4. Height of propagation above ground surface
5. Reflections
6. Meteorological conditions.

2.4 MEASUREMENT OF NOISE LEVELS

In Australia, the noise levels produced by vehicles have been defined to find existing traffic noise levels (Commonwealth of Australia, undated). When measured under careful, specified test conditions, the following maximum noise levels can be used to describe the existing noise environment.

Passenger cars.. 96 dB(A)
Motor cycles... 100 dB(A)

		diesel	non diesel
Truck or bus with gross vehicle weight < 3.5 Tonnes		91 dB(A)	78 dB(A)
Truck or bus with gross vehicle weight 3.5 < or > 12 Tonnes		93 dB(A)	84 dB(A)
Truck or bus with gross vehicle weight > 12 Tonnes		95 dB(A)	85 dB(A)

The test sites are level, covered with hard material (E.g. asphaltic concrete), providing acoustic reflection, and in open air. For cars and motor cycles, the site is rectangular with no side within 3 meters from the test vehicle, and for trucks and buses it is square with sides at least 45 metres long with an inner circle of 12 metres radius. Only essential equipment are permitted in test areas as required by the specifications of NAASRA.

According to the SAE specifications, for cars and motor cycles, the test microphone is placed at the height of exhaust pipe outlet, facing the outlet at 45 degrees to its axis and 525 mm from the outlet. For trucks and buses, the microphone is set at 1.2 metres off the ground, facing the outlet.

For the stationary noise test, the vehicle is kept stationary with its transmission in neutral, and the engine at normal operating temperature to check the exhaust noise. For cars and non diesel trucks the engine is run at three quarters of the engine speed at maximum power. For motor cycles, one half the engine speed at maximum power is used. A special procedure is designed for trucks. Their engines should have to be accelerated rapidly, up to their governed speed, stabilised at that speed, and then decelerated rapidly.

Noise generated by heavy vehicles deserves particular attention as this is often used as a surrogate measurement for many other nuisances created by them. These nuisances include interference with other vehicles, smell, vibration, tyre noise, gear noise, their size, and the heavy loads carried by them, in addition, very high engine outputs (E.g. 400 horse power) in some cases.

NAASRA (1974) provides a guide for noise measurement exercises. According to this guide, schematically shown in figure 2.2 where two areas are expected to have average noise levels within 3 dB(A) of each other, they could be covered by one measurement site. For residential annoyance studies, the guide recommends that measurements be taken at one meter away from the facade of the residential amenity facing the roadway, but not closer than five metres from the nearest traffic lane. This approach avoids traffic stream distortions and improves the ease of the estimation. If it is not possible to get within one meter of the facade, the guide recommends that the measurements be taken in an equivalent position where there is no sound reflecting surface within 15 metres of the measuring instrument.

The L_{10} readings for example would need 3 dB(A) to be added to account for facade reflection. The measurements taken within the rooms be given specific conditions to avoid duplication. The measurements should only be taken when the road surface is dry, and when either the average wind speed at 1.2 metres height is below 2 metres per second, or where the wind direction is more towards the instrument than along the road, as NAASRA (1980).

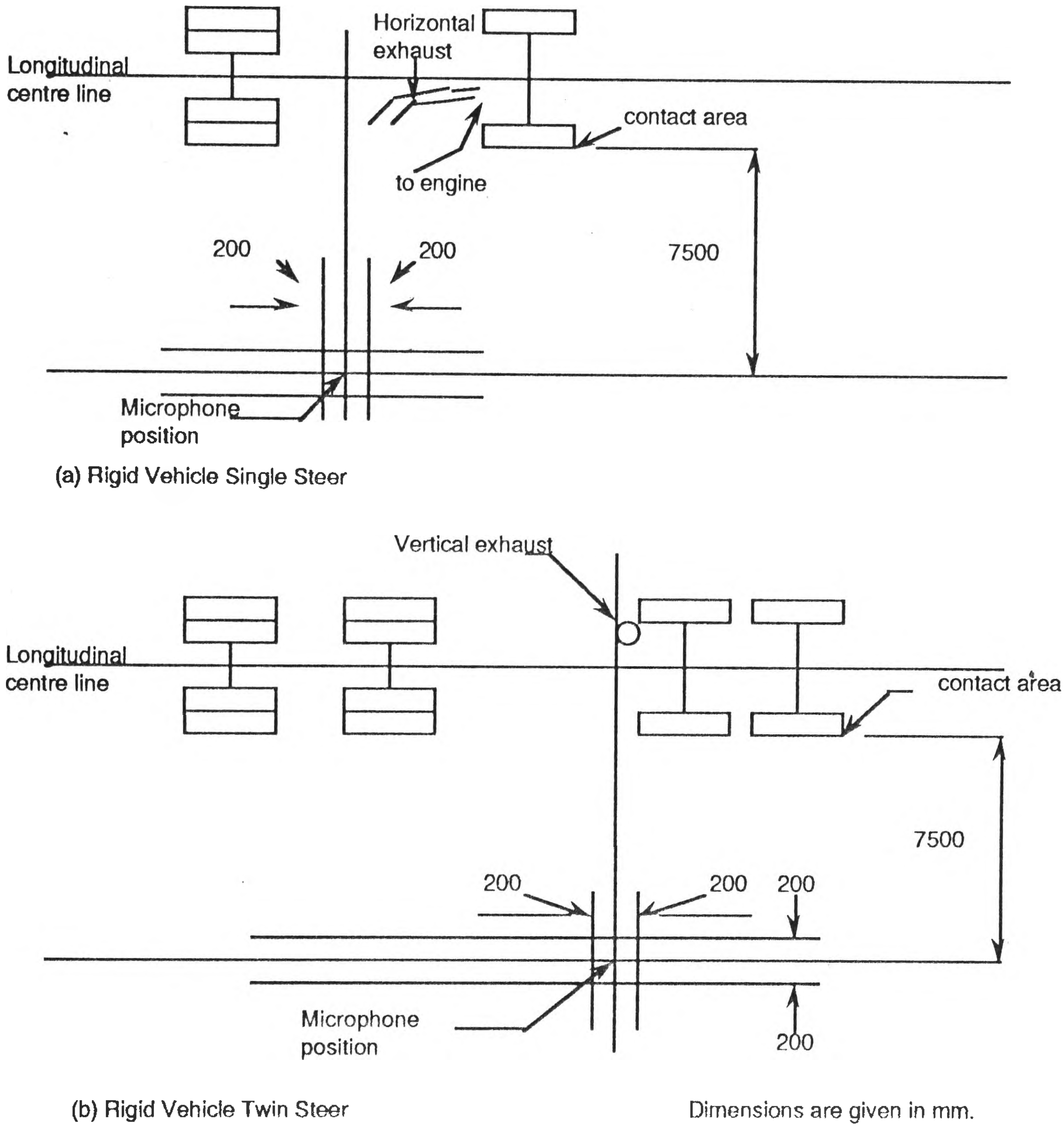

Figure 2.2 Schematic plan for placing test microphones for two differing exhaust configurations (After Commonwealth of Australia, undated).

Many prediction models have been developed in the UK, USA and in Europe taking into account measurements alongside freely flowing traffic [Delany (1972); Gorden and et. al., (1971)]. The formula developed by Delany has been shown to produce an accurate prediction for freely flowing traffic on arterial roads. This formulae takes the form:

$$L_{10} = K_1 + A_1 \log Q + B_1 \log V + C_1 p - D_1 \log d \quad (2.12)$$

$$K_1 = 31, A_1 = 8.9, B_1 = 16.2, C_1 = 0.117, D_1 = 14.7$$

where

Q = Total hourly flow rate of vehicles (veh/h)

V = Average speed of vehicles (km/h)

P = Percentage of heavy vehicles (%)

d = Distance between the nearside traffic lane and the observer in feet.

The traffic conditions on which the above method was developed is different from Australian urban roads. However, measurements of traffic noise in the Sydney metropolitan areas have shown that a formula of this type is valid for traffic on level roadways, and as freely flowing as is possible in the urban area (Burgess, 1977).

2.4.1 Modifications to Delany's Model

The previous formula developed by Delany has the term V, which is difficult to determine in urban areas, and hence it has been omitted and the value for C was doubled as determined by Delany. However, the values for K, A and D were Delany's version. The modified model has given a coefficient of multiple correlation of 0.93 and a standard error of estimate of 1.6 dB(A) was found using the following formula:

$$L_{10} = K_2 + A_2 \log Q + C_2 p - D_2 \log d \quad (2.13)$$

where

$$K_2 = 56, A_2 = 10.7, C_2 = 0.3, D_2 = 18.5$$

The predicted noise levels for a 6 lane, two way road are shown in Figure (2.3), for a position 10 Metres from the centre of the flow of the near side lane (common boundary of the residential properties is usually about 10 meters). The percentage of heavy vehicles is taken as 10%. This prediction method has been shown to be not valid for flows less than 500 vehicles per hour (Burgess, 1977). It is very easy to understand that how many people are disturbed due to traffic noise, as there are many roads with similar and even greater traffic flow as the one considered. However the values for L_{10} assume freely flowing traffic on a level road way, and if the traffic is accelerating up a grade or stopping and starting at controlling traffic lights, the levels would be approximately 5 dBA higher. In addition, if there are reflecting surfaces nearby and the percentage of heavy vehicles is greater, the L_{10} would be even greater (Lawrence and Burgess, 1977). Figure 2.3 shows the predicted L_{10} values compared to the acceptable values.

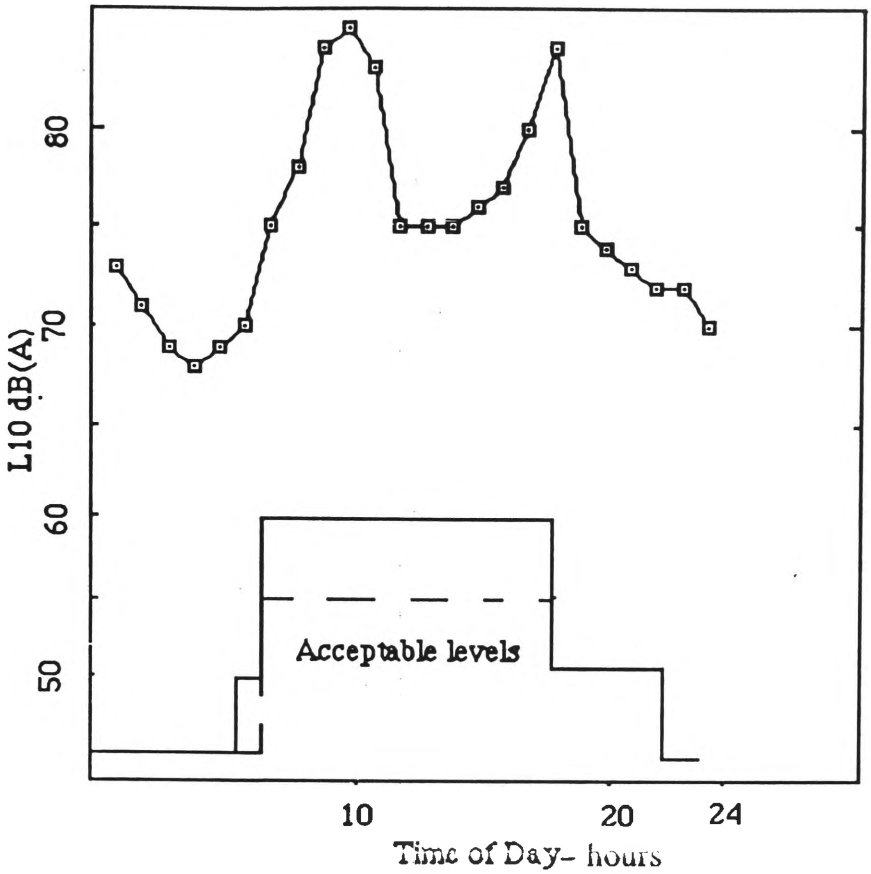

Figure 2.3 Predicted value for L_{10}, compared to acceptable levels determined by AS 1055 (After Burgess, 1977)

2.5 Noise Emission by Individual Vehicles

By making a simultaneous voice commentary, assisted by video technology and still photography, the actual values present in a traffic mix at any time may be identified. With high flow rates, the vehicles actually identified are limited to "Other than passenger cars," with exception to exceptionally noisy cars.

If the L_{10} or L_{eq} level is superimposed on a sound level recorder trace of a traffic noise sample, any noise peaks above this level are from the vehicles that are making the most significant contribution, Figure 2.4. It has been found that, on average, 85% of noise peaks more than L_{10+5} dB(A) was produced by medium and heavy commercial vehicles, although they contributed an average of only 10% of the vehicle mix in the 21 site samples studied. The remaining noise peaks were emitted by the motor cycles and by cars with modified or faulty silencers, (Burgess, 1977).

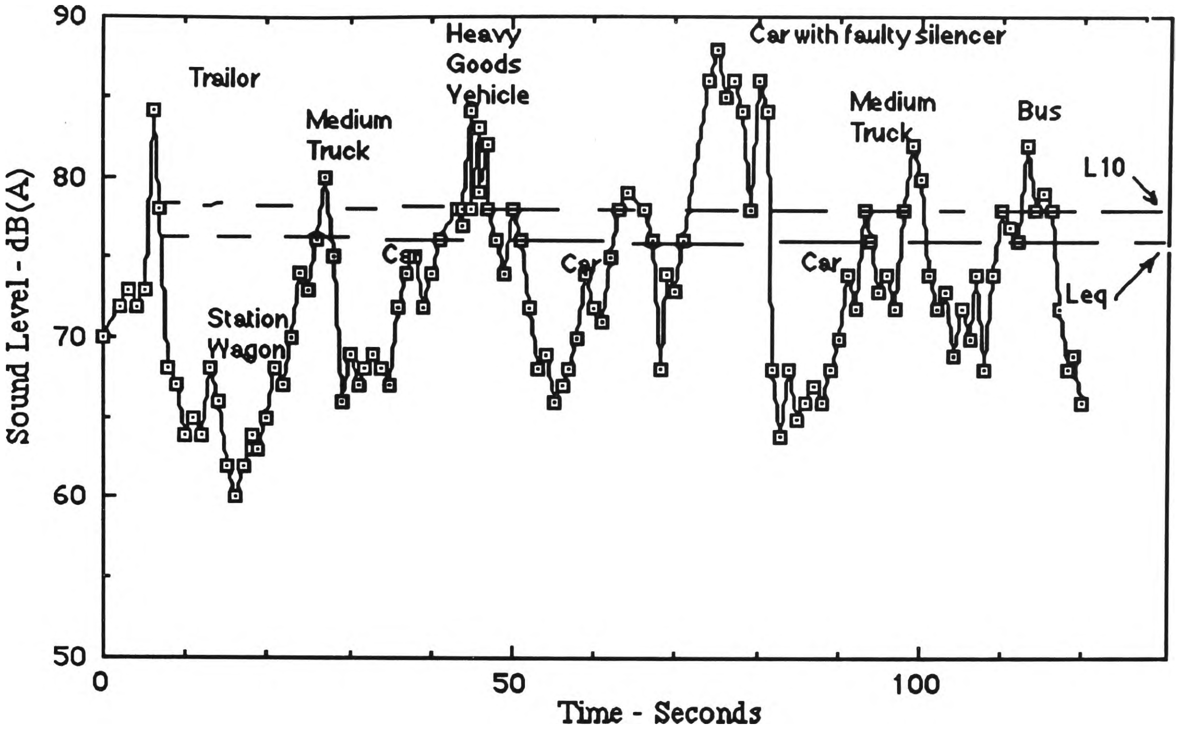

Figure 2.4 Contribution of individual vehicles to traffic noise. (After Burgess, 1975)

2.6 PREVIOUS RESEARCH RELATED TO QUIETER VEHICLE

Much research work has been carried out in relation to the achievement of a "Quiet Vehicle" phenomenon. The most difficult type of vehicle to silence is the heavy vehicle (HGV), and the articulated tractor - trailer is the worst among them, due to fact that they have to provide additional power to obtain sufficient power with the power to weight ratio. Commercial interests in the freight industry seek to maximise the carriage size, and construction limitations and motor traffic regulations restrict the width and the length of the vehicle. Due to the interaction of these constraints, the spaces of the tractive unit must be minimised. Hence, there will be insufficient space in the tractive units of the heavy vehicles for the additional silencing required, and for additional insulation which may affect engine cooling.

In the UK, a "Quieter Heavy Truck" Programme was carried out by the Transport and Road Research Laboratory (TRRL), in collaboration with the British Leyland, Forden, and Rolls-Royce motor companies. The objective of this programme was to quieten existing heavy vehicles, at least by another 10 dB(A). A redesigned Rolls-Royce Eagle engine in a Forden heavy vehicle prime mover unit was developed which had given 83 dB(A) on a drive past test, and an experimental Leyland Buffalo prime mover with an engine enclosure and special exhaust and cooling packages had shown 79 dB(A) on the drive past test. Similar noise levels have been achieved with vehicles in Europe and the United States (Watkins, 1974).

If the heavy vehicle noise can be decreased by 10 dB(A), an accompanying reduction in L_{10} has been estimated to be 2 dB(A) to 9 dB(A), depending on the percentage of trucks in the traffic flow (Watkins, 1974). A reduction in car noise levels of 5 dB(A) would bring about a reduction of L_{10} values of 6 dB(A) to 10 dB(A). Therefore, there exists a strong requirement to introduce quieter trucks as well as quieter cars in future, to mitigate increasing traffic noise levels. In 1975, heavy tractive units were produced which could achieved British Standards (B.S.) noise levels of 85 dB(A). Eventhough the standard for the quiet vehicle program has been set at 80 dB(A), it can be seen the Figure is not overly ambitious.

Although heavy vehicles are the noisiest group of the whole vehicle population, a costly research and development program could be justified only if the results of quietening them are shown to have a significant effect on the overall noise climate. For studies of this aspect, an analytical programme developed at the TRRL of UK can be employed with satisfactory results.

Table 2.1 gives the reduction of noise levels for four different values of traffic flow and for four different proportions of cars and lorries (all the commercial vehicles above 4 tons GVW). The first set of values gives the reduction if the noise levels relevant to the lorries were reduced by 10%, and the second set of values gives the additional reductions if the car noise levels were also reduced by 5 dB(A), in addition to the reduction of the lorry noise levels. The above values were calculated by assuming a free flow traffic condition along a two lane, single carriageway road, and the observation were done at a point situated 10 meters away from the nearside curb, and propagation over grassland. The actual values quoted here would vary according to variations in these basic assumptions.

Table 2.1 Reduction of L_{10} values due to the reduction of individual heavy vehicles. (After TRRL, 1974)

	Reduction in L_{10} dB(A)			
Flow (veh/hour)	10% Lorries	20% Lorries	40% Lorries	80% Lorries
200	1.4 (5.6)	2.5 (6.3)	4.5 (7.3)	8.4 (9.3)
400	1.4 (5.6)	2.5 (6.4)	5.1 (7.9)	8.8 (9.6)
800	1.5 (5.9)	3.1 (7.0)	5.9 (8.8)	9.0 (9.8)
1500	2.0 (6.4)	4.2 (7.8)	6.3 (9.1)	9.0 (9.8)
2000	2.3 (7.0)	4.8 (8.4)	7.1 (10.0)	9.3 (10.2)

When the above figures are taken into perspective, it helps to understand that a reduction of about 10 dB(A) means somewhat halving the subjective loudness of the noise, and from there a further reduction of traffic noise by 5 dB(A) is comparatively quite considerable. As it is expected, the above table shows that when the percentage of heavy vehicles quietened is larger, the reduction in noise levels also becomes comparatively larger, and this applies right down to a content of about 20% of lorries, even if all the lorries are quietened.

2.6.1 Previous Research Related to Tyre - Road Interface

Coarse texture is incorporated into the surface of roads primarily to disperse water rapidly, and is essential to maintain skid resistance at high speeds. Unfortunately, the deep texture brings with it increased tyre noise and so compromising values have to be sought.

To quantify the problem, measurements have to be made on a range of different textured roads, at high and low speeds, at braking and accelerating conditions. Results have shown predictably that different relationships exist for bituminous and grooved concrete surfaces. Accordingly, it has been shown by Salt (1979), that a unique linear relationship exists between tyre noise emanating from a road surface, and the effectiveness of its texture for high speed skid resistance. This finding enables a policy on texture requirements to be formulated, which are equitable to both bituminous and cement concrete interests and which attempt to strike a balance between road safety and noise.

The expected reductions from the quieter vehicle programme can only be achieved at 60 to 80 km/h levels, only if the noise emitted due to the tyre / road surface noise does not exceed 77 dB(A) (Watkins, 1974). If this limit is relaxed, that would lead to the vehicle emitting more than 80 dB(A). When the speeds is doubled, the tyre and road surface noises increase by 10 dB(A). But, if it is expected to reduce road surface noise by altering the road surface texture to be smooth, the skidding resistance is affected and hence accident risk will be increased. Measurement of braking force coefficient indicates that a smooth tyre on smooth surfaces would be very unsafe at high speeds, and hence it will not be a solution to the noise problem. On rougher surfaces, the smooth tyre brake force coefficients were not so different from those of patterned tyres, and hence, the smooth tyre-rough surface combination can be considered as a possible solution to the tyre / road surface noise problem. This solution will however, impose a great responsibility on the road authorities to maintain their road surfaces in as new condition. Because of the cost of such maintenance, it would be an intolerable addition to the already enormous road budget, and the smooth tyre cannot be considered as a justifiable solution to tyre noise (TRRL, 1970).

According to experiments carried out in the UK, some highway type tyres have been recommended, which only just exceed the target noise levels. The use of such tyres would raise no safety problem, and it seems advisable as a short term objective to consider what practical modifications could be made to this sort of tyre, to reduce the noise at high speed by 2 to 3 dB(A).

An alternative approach to meet about 80-85 dB(A) level on dry roads would be to design the vehicle with a maximum operating speed of 80 km/h, or else to impose the Heavy Goods Vehicle (HGV) speed limit on designated areas affected by traffic noise, as 80 km/h. Since for economic reasons and competitiveness, the quiet lorry has to achieve the maximum speed limits enforced by the roads' authorities, and existing political problems seem to be the most likely hindrance to the choice of an 80 km/h speed limit for the HGV s. Table 2.2 shows the noise levels measured for various surface combinations at different speeds, and on wet and dry conditions.

Table 2.2 Effect of different road surfaces on noise levels during an acceleration test (After Watkins, 1970).

RANGE OF SOUND LEVELS MEASURED IN INVESTIGATION							
TYRES	LOAD	SOUND LEVELIN dB(A) SPEED RANGE 40-100 km/h					
		SURFACES					
Cross ply - (16-ply) Tyre Pressure 620 KN / m2		Smooth concrete		Coarse Quartzite Surface Dressing		Motorway Asphal t	
		dry	wet	dry	wet	dry	wet
Smooth Natural Rubber	U L	64 - 72 NT	67 - (81) NT	64-77 66-78	78-86 NT	65-79 66-(81)	78-88 NT
Smooth High Hysteresis Rubber	U L	61 - 74	70 - 83	64-77	78-89	66-80	81-90
Highway Type B 7 Ribbed natural Rubber	U L	64 - 77 65 - (78	75 - 83 NT	64-78 66 (79)	76-84 NT	67-83 67-(83)	79-85 NT
Highway Type A 5 Ribbed Natural Rubber	U L	64 - 79 64 - (80	77 - 87 NT	65-78 67-(79)	75-84 NT	67-83 67-(83)	79-88
Traction Transverse Grooved Natural Rubber	U L	65 - 83 69 - (88	75 - 89 NT	65-81 67-(82)	77-87 NT	68-83 67-(86)	NT 79-91
Traction Transverse Grooved High Hysteresis	U L	62 - 82	73 - 90	66-79	79-89	68-83	NT 78-90

U.......Unladen Lorry 5.6 Mg (Tonnes) . NT.......Not Tested .
Load......L.......Laden Lorry 13.2Mg (Tonnes). ( ).......Extrapolated Results.

On the wet surfaces at 100 km/h all the tyres emit noise levels in excess of the limit [77 dB(A)].

During this test it had been noticed that no tyre surface combination generated levels in excess of 68 dB(A), which is a comfortable 9 dB(A) target below the target [77 dB(A)] set. It seems clear that with wet road surfaces the tyre to surface noise target cannot be met without some major innovations in tyre technology. However, it is indicated that if the surface can be drained rapidly, tyre - surface noise can be reduced.

If the noise from a vehicle to be 80 dB(A) or less the tyre surface noise must not exceed 77 dB(A). Any relaxation of this limit might lead to the vehicle emitting more than 80 dB(A). TRRL in collaboration with the British Rubber Manufacturers Association, the noise characteristics of tyres with four different tread patterns rolling on three different surfaces, as shown in Figures 2.10. These have been chosen because they were thought to represent the range of possible tyre road surface combinations from the noisiest to quietest available during the study period.

Experiments done by Dunlop Tyre Manufactures (Anon, 1990), shown the advantages of certain types of road surfaces. The tyre variables investigated include the effects of sectional width, and of inflation pressure. Accordingly it has been indicated that maximum possible tyre road noise would be generated by a vehicle of given weight, travelling at a given speed, by optimising both tyre and road macro texture parameters.

2.6.2 Tyre noise generation

According to past surveys conducted in Australia related to vehicle noise available upto 1975, the engine and exhaust contributed about 60%, the cooling fan system about 30%, and tyres about 10%, to the overall traffic noise. According to the latest developments of automotive technology of the century, the engine's contribution was brought down by 25%, exhaust and cooling systems by further 25%, but the tyres are still contributing heavily to the vehicle noise (Anon, 1990).

In the official noise tests on trucks, accelerating from typically 25 to 45 km/h, tyres made a minority of contribution, but above 50 km/h speed, tyre noise had remarkably increased. Hochrainer (1990) stressed that it was not simply the tyres that produce the excess noise, but a combination of tyre and road surface (Kennett, 1990), and as much as 10 dB(A) difference could be recorded by the same truck tyres running on wet and on dry concrete or drain asphalt surfaces. Eventhough the draining asphalt (open graded texture) is quite expensive, if community really need a lower traffic noise they have to make a contribution to the laying of sound suppressing surfaces such as draining asphalt.

There are three mechanisms responsible for tyre noise generation:

(a) impact between the tyre and load
(b) micromovements of rubber on the road
(c) air pumping of the tread pattern.

Three related resonances involved are:

(a) those of the tyre
(b) the air in the tyre
(c) the tread elements (Samuels, 1982).

The impacting mechanism of the tyre and the road was studied by using an accelerometer inserted inside the tyre which showed a change in acceleration as the tread entered and left the contact patch at a speed of 113 km/h (Richards, 1973). Laying open graded asphalt (Carpeting) to soften the impact reduced the noise level of a block pattern tyre by 8 dB(A) at 48 km/h - 113 km/h speed (Richards, 1973). Glass plate studies conducted by Richards (1973) showed the micromovements of the tyre tread whilst moving were a major cause of tyre noise.

As the speed falls, the particular harmonic passes through resonant frequencies and the level of harmonics (tyre noise related) rises. Similar behaviour by several harmonics confirms that the existence of the resonances. There is only a slight peak level of tyre noise harmonics for both the 8 mm tread depth tyre at 1000 Hz, and for the 1mm tread depth tyre around 1900 Hz. This shows that the stroking mechanism is not a dominant mechanism in tyre tread depth noise. Figure 2.5 shows the wheel harmonics generated at straight ahead rolling of the tyres.

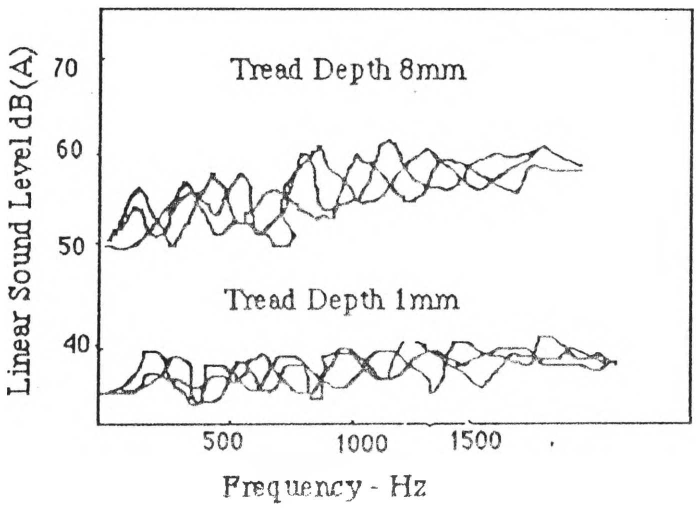

Figure 2.5 Frequency components of the noise tracked at harmonics of wheel rotation for straight ahead rolling. (After Richards, 1973)

Another mechanism of air pumping was discussed by Hayden (1971) and his theory was further developed by Samuels (1976) which concluded that impacting mechanism of tyre tread is a dominant factor. The impacting mechanism of tyre tread pitch, mean aggregate spacing and relevant noise frequency generated are given in figure 2.6.

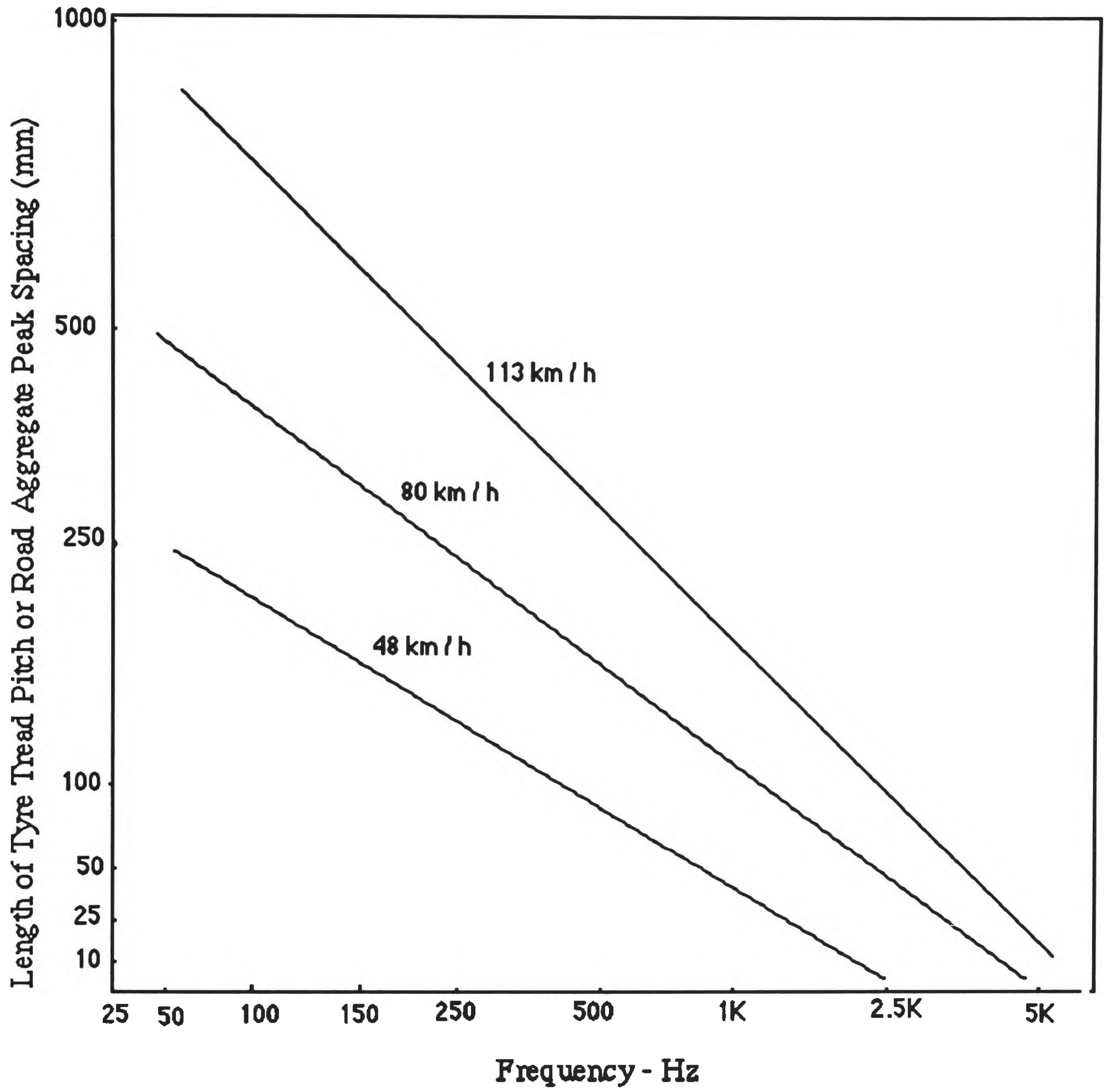

Figure 2.6 Relationship of length of a tyre tread pitch or the mean aggregate spacing of the road, vehicle speed, and corresponding noise frequency generated (After Samuels, 1976)

Air pumping is dominant in the case of treads that can trap pockets of air on smooth road surfaces. The tread type used on truck tyres have shown air pumping behaviour to a large extent, and is much noisier than the new tyres. Micromovement of tread and tread resonances do not generate as sharp resonant noises as cornering squeals.

Concerning road surfaces, an increased wet grip can be obtained with less rolling noise for the cars and the trucks, with open-graded surfaces. In the design of this non polishing surface, a balance between surface course enough to give adequate bulk water drainage, and fine enough to give a minimum noise has to be sought.

Evidently, both the tyre designer and the road designer have to understand each other's ideas very carefully, when making their decisions regarding the tyre noise for optimum environmental noise mitigation aspect.

2.7 RESEARCH AT TRANSPORT AND ROAD RESEARCH LABORATORY, UK

Transport and Road Research Laboratory of UK had conducted a series of tests to determine the tyre noise generation. Results of some of these tests have been published. According to one of the above tests, the noise frequency (independent of the speed) is increased, by 1 KHz, when the tyre squeals on cornering. The squeal frequency will further increase as the tread depth increases, as discussed by Trivisnno et al., 1967). The tyre squeal is the tread element resonance. During the investigations conducted to find out the facts regarding dominant frequency peaks, the average output of three microphones was used for the measurements of the noise levels. This has been achieved by locking the tracking filters to a particular harmonic noise caused by the wheel rotation, and by varying the tyre speed on a drum between 80 and 115 km/h. Figure 2.7 shows the cornering squeal with the slip angle as shown by Trivisonno et al.(1967).

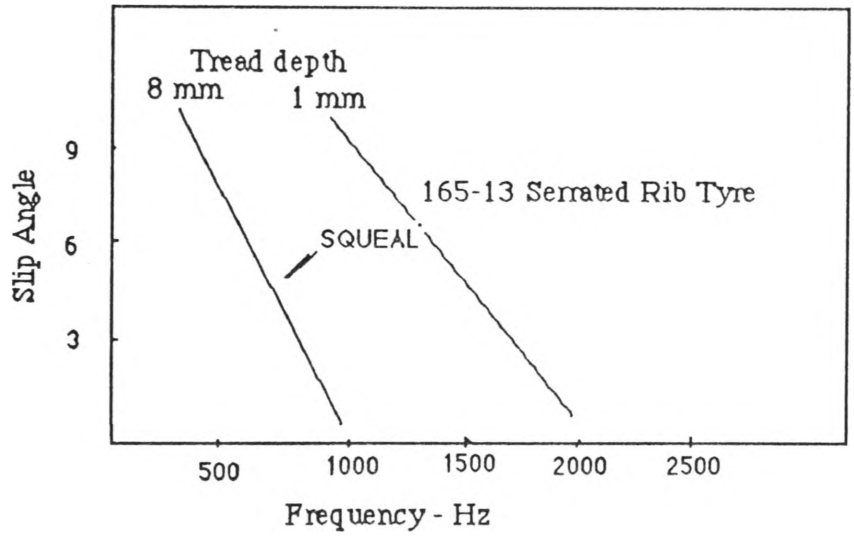

Figure 2.7 Increase of cornering squeal with the slip angle. (After Trivisonno et al., 1967)

In order to determine to what extent there exist the frequency peaks in the straight ahead rolling noise, corresponding to the estimated cornering squeal as 0^0 Slip Angle is approached, the following results were obtained with tyres with 8 mm, and 1 mm tread depth, and serrated ribs and microslot tread patterns.

The results obtained for truck coasting noise for various tyre - road combinations (TRRL, 1973) are shown in Figure 2.8 below. This shows the coasting noise levels in dB(A), for a laden truck of 13.2 Mega Grams (13.2 tons), travelling at 100 km/h, measured at 7.5 meters from the centre of the vehicle. Three dry surfaces, surface were used: a motorway surface, a smooth concrete surface, and a coarse quartzite surface. Three types of tyre designs were used also; blank tread, ribbed tread, and the tractive tread patterns on 10.00 X 20 (tyre widths = 10 inches and rim diameter = 20 inches) cross ply tyres. Blank tread type is one of full tread thickness tyre without a tread pattern.

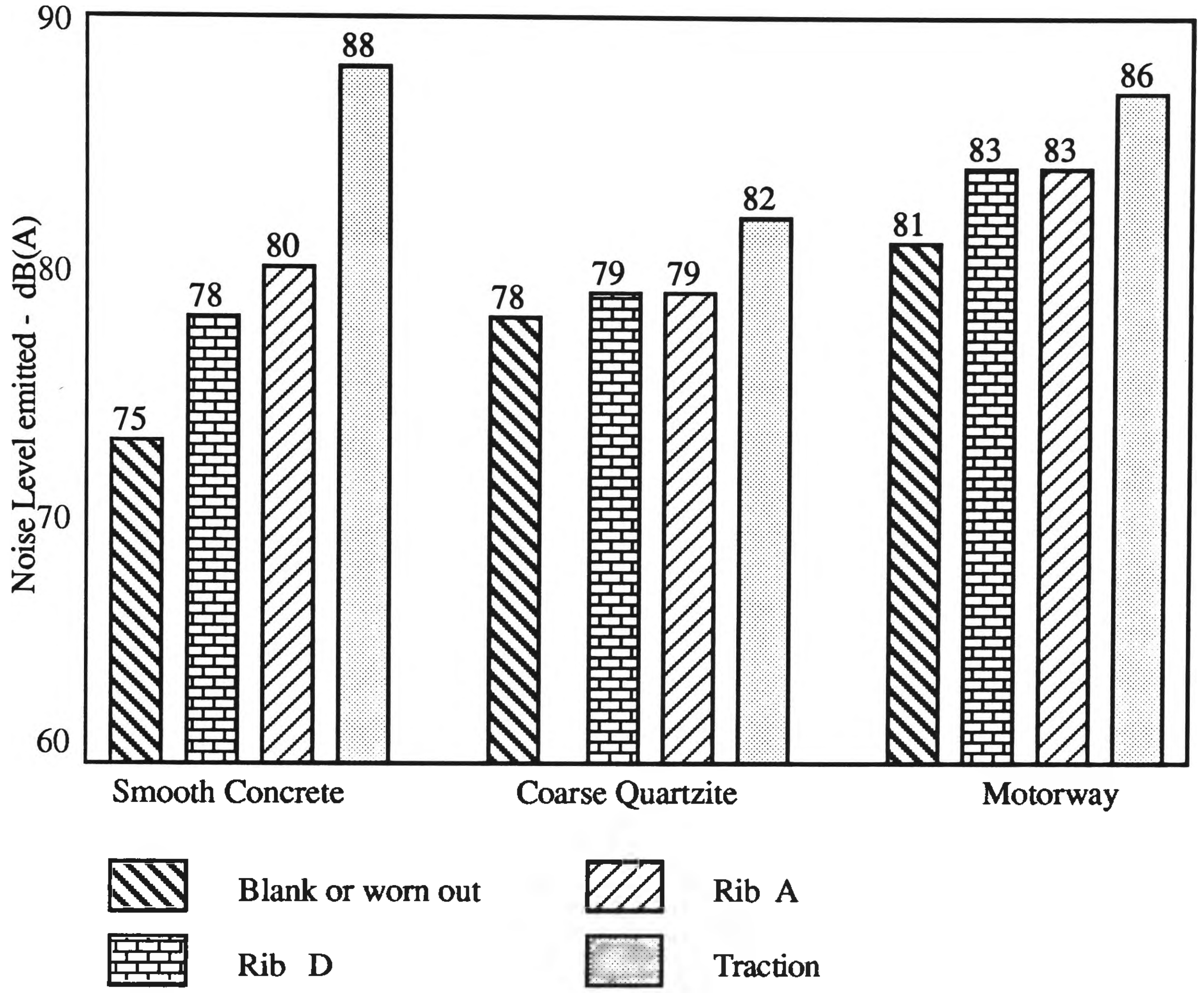

Figure 2.8 Coasting noise for various tyre - road combinations. (After TRRL, 1973)

Accordingly, the smooth concrete surface shows a much greater contrast in tread pattern road noise than the surface with the roughest macro texture (coarse quartzite) which is the texture of road surface used for maximum water drainage. The ribbed tyres have shown to be 1 to 2 dB(A) noisier than when operating on on smooth concrete, and traction tyres are about 3 dB(A) noisier than ribbed tyres. Therefore, the potential improvement in dB(A) levels by tread pattern changes can be relatively smaller for course surfaces.Tyres of the traction type of tread pattern appear to be about 6 dB(A) quieter on the coarse quartzite than on the smooth concrete. It appears that the road surface texture is barring the tread effect on vehicle noise. The traffic noise generated on the coarse quartzite road surface appears to be about 3 to 4 dB(A) quieter than on the motorway road surface for any type of tyre tread pattern. Other related parameters were also tested.

2.8 TYRE AND ROAD SURFACE VARIABLES

There are a number of variables which contribute to the tyre - surface noise. Figure 2.9 shows a tyre noise model which explains the variables related to tyre noise.

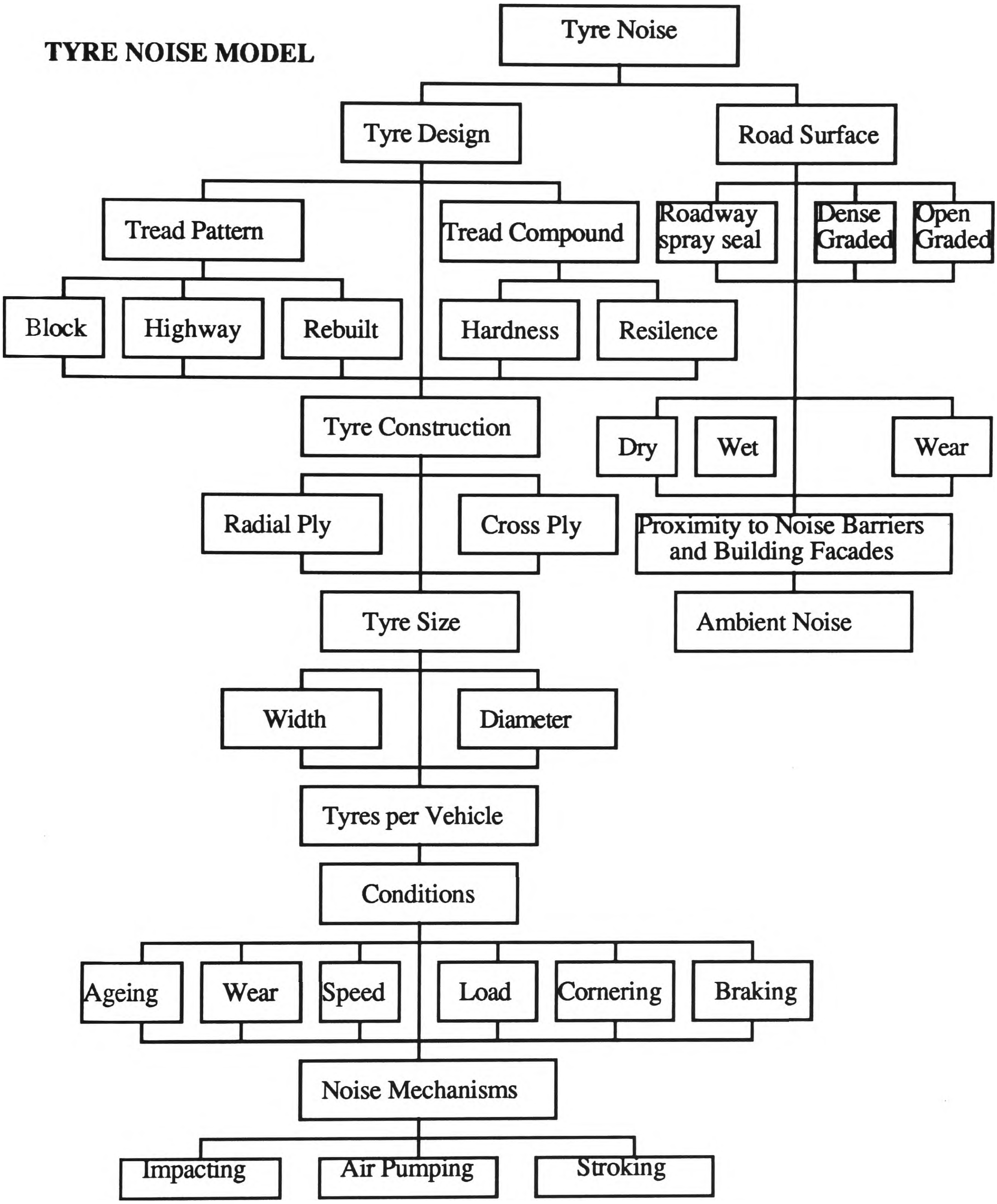

Figure 2.9 Relationship of tyre and road surface variables. (Ref. Field work by author)

Design, construction, size, number of tyres per vehicle, condition of tyre and the ride and the noise mechanisms are the major contributors related to tyre. Type of road surface, condition, proximity to building facades, and the ambient noise are related to road surface. These variables are shown in Figure 2.9. The above mentioned variables have been described below.

(a) Wet Road

If rain water lies on the road surface, the noise generated from travelling vehicles can be 7 - 11 dB(A) greater than when the surface is dry. However, if enough drainage is provided to drain the surface water from the road way, the wetted surface noise is almost identical to the dry surface noise (Nelson, 1973).

(b) Sectional Width of Tyre

Figure 2.10 shows that the effects of the sectional width of a tyre at constant load on the 13 inch - rim diameter size using serrated rib tread type tyres. Accordingly, tyres with 145 mm sectional width are 2.5 dB(A) quieter than ones with 185 mm sectional width. As the sectional width decreases, the tread diameter also decreases. Therefore, the diameter effect opposes the tread width effect (Nelson, 1973).

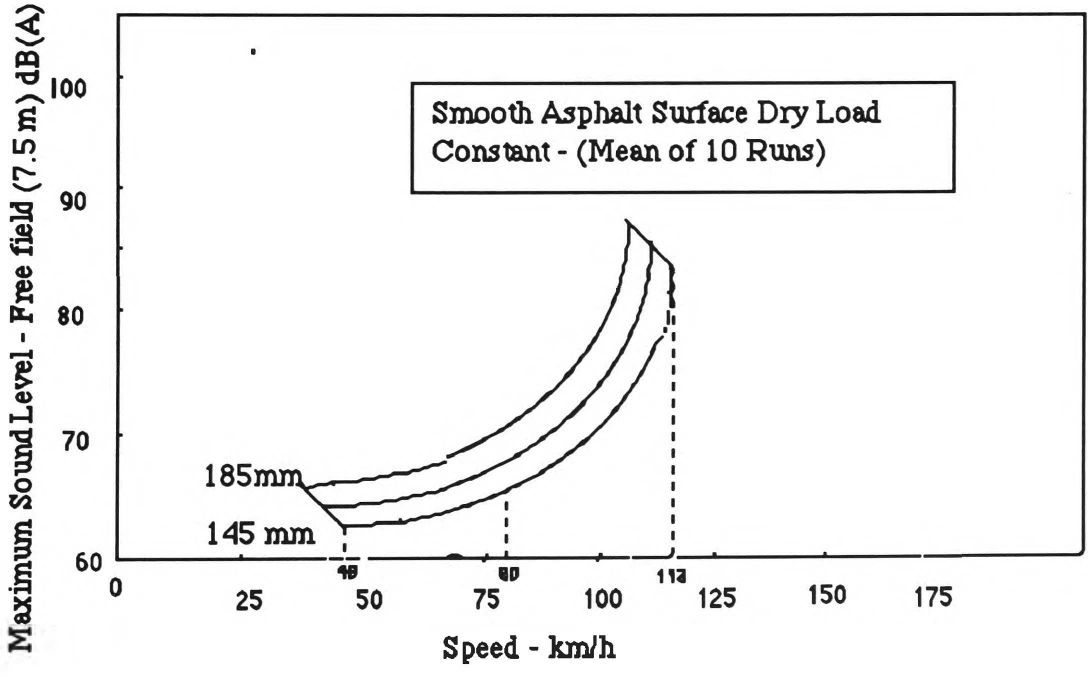

Figure 2.10 showing the lattice plot effect of sectional width, constant aspect ratio. (After Nelson, 1973)

(c) Tyre Diameter & Wheel

During drum tests (tests carried out in the laboratory using a test rig consisting of drum type rollers on which the wheels of the test vehicles were driven) for tyres with the same block pattern tread and the same sectional width, the tyres of 10 inches rim diameter were found to be 1.2 dB(A) noisier than 13 Inches diameter tyres, and lighter alloy wheeled tyres were 1.5 dB(A) quieter than the steel wheeled tyres. The relationship between the tyre rim diameter and the noise generated by a particular type of a tyre is found to be inversely proportional to the rim diameter (Nelson, 1973).

(d) . Tyre Construction - Radial Ply or Cross Ply

The tyres of radial ply and cross ply types were tested on the drum apparatus, both having basically the same tyre block pattern tread, and the same width. The noise levels generated were measured at three microphone positions and averaged. Accordingly, radial tyres were found to be 0.7 dB(A) quieter than cross ply tyres (Nelson, 1973). But, where the load bearing capacity and cost is concerned, cross ply tyres are preferred for use with heavy goods' vehicles instead of radial ply tyres.

(e) Speed

Truck tyre tests at different speeds, showed an average 10 dB(A) increase with doubling of speed (Nelson, 1973). This corresponds to approximately 2.5 to 3.5 dB(A) increase per 25% increase in speed.

(f) Load And Inflation Pressure

Automotive Engineering (1972) - [Journal of the Society of Automotive Engineers - USA] reported that if the load is kept in the 75% - 100% range of the maximum rated load under the scheduled tyre pressure, the sound level generated does not change appreciably. But overloading by 0.69 - 2.01 Mg per tyre, on cross bar type tyres will increase the tyre noise at a rate of 6 to 8 dB(A) compared with rib type tyres. The rubber manufacturer's association of UK pointed out that, at constant load, an increase of 103 kPa (15 psi) has shown a noise decrease of 0.5 dB(A).

(g) Tyres Per Vehicle

Doubling the load and number of wheels will raise the noise levels by, approximately 2 dB(A) (Tetlo, 1973).

2.9 CONCLUSION

It is clearly evident that the noise reduction at source is the prime solution to the traffic noise problem area. The vehicle speed, flow rates, road texture, road condition, and the tyre and tread design are controllable factors among the variables which contribute to the traffic noise. Hence the attention should be drawn to find optimum levels to control these in order to mitigate the traffic noise levels. This thesis is highly concerned with the above controllable factors in addition to developments in Noise barrier technology, to achieve its objectives in more economical, environmentally friendly, more feasible and beneficial way.

CHAPTER 3

TRAFFIC NOISE MEASUREMENTS AND EFFECTIVENESS OF NOISE BARRIERS

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TRAFFIC NOISE MEASUREMENTS AND EFFECTIVENESS OF NOISE BARRIERS

3.1 INTRODUCTION

Sound pressure occurs as a result of periodic mechanical wave disturbances of a medium (air), within the range of frequencies and amplitudes to which human hearing system responds. The sound pressure fluctuates below and above atmospheric pressure and moves at about 340 m/s at 20^0 C. Impervious objects such as mounds will avoid the direct (line-of-sight) transmission of the sound waves, although they may be bent or diffracted past such objects. Sound waves are quite susceptible to diffraction past edges. Most trees (vegetation) only gently dissipate sound, and should not be relied upon for noise reduction, (Lay, 1981).

This chapter is devoted to the field work done by the author in relation to the noise barrier technology as a major strategy in traffic noise mitigation exercise. Traffic noise measurements were obtained at test sites selected from the Wollongong City Council area of the Illawarra region of New South Wales where there exists natural earth mounds, road side vegetation, different types of artificial and natural noise barriers. Actual attenuation obtainable from these barriers have been pointed out, and accordingly, the required modifications were suggested for better results.

In addition, the acoustic theory related to noise such as response of human ear to the logarithmic scale of the sound pressure level, sound intensity level (Decibel scale), loudness, weighting factors for different sound pressure levels, equivalent continuous noise level, daily exposure to noise level exceeding 10% of the time between 0600-2400 hours (18 hour period), day and night noise levels, addition of different noise levels, noise ratings, acceptable noise levels, community annoyance levels, noise levels related hearing damages, masking effect, critical band width and it's contribution to the actual noise levels, and the measurement of interference to speech due to noise, also are briefly discussed herein.

3.2 ACOUSTIC THEORY RELATED TO NOISE MITIGATION

A large a number of theories related to acoustics is available. But, only a few of them related to the exercise of traffic noise mitigation are discussed herein. A brief summary is given here regarding the sound wave, it's characteristics, it's motion and transmission in different mediums such as air, water and solids.

3.2.1 Sound Wave and it's Nature

The motion of the sound is somewhat similar to the ripples appear in a pond when a stone is thrown into it. A sound wave is characterised by the pressure differences superimposed on atmospheric pressure, and due to the accompanying oscillations of the air particles. The pressure acts in all directions at a point. Due to above nature of the sound waves, it is described either as a scalar quantity by the people who are interested in vector analysis, or as a hydrostatic pressure by those familiar with fluid dynamics.

Eventhough a disturbance travels out from it's source, the medium (air) through which it is transmitted does not travel, but is simply oscillates about a fixed point. The speed of the sound (V) can be denoted as the rate at which a message travel and which for the air at 20^0 C are about 340 m/ sec (meters per second). As the medium is massive and elastic, the wave travels and the speed of the sound depend upon these two qualities (Turner and Pretlove, 1991).

As the energy involved in outward transmission of sound from a sound source is very small, only a little effort is required to make a sound. If the pressure disturbance is considered in these dimensions, the pressure disturbance will diminish as the wave travel outwards it's source since the initial finite amount of energy is gradually spread over a large area.

The sound wave acts in same nature as the light waves, and is subjected to reflection, refraction, and diffraction. When the acoustic sound wave impinges on a boundary between air and a different material such as a masonry wall, or where there is a change in section such as a "T" joint of a pipe, the reflection occurs in a similar way as a rubber ball jump and bounces on the ground, due to change in impedance, when it touches the boundary wall or ground. The bending or deflection of the wave causes the "Refraction" of the wave, due to changes in the wave velocity. Usually, there are only minor changes caused due to the reasons such as the changes of temperature and wind gradients. The gradual spreading out of the sound wave in an angular sense, is called the "Diffraction" (E.g. when a parallel sound beam travelling though a pipe reaches an open end of the pipe, it will become diverged, and then instead of travelling as a parallel beam, it will spread out). The amount of divergence will depend upon the acoustic wavelength ratio of the diameter of the pipe. The sounds with a very short wavelength will show a very small divergence and vice-versa. This divergence is a very important factor in designing of the noise barriers, to mitigate traffic noise.

Usually, the harmonic waves are used when the sound is analysed, because of these pressures that vary sinusoidally with time and space. The variation in time leads to the concept of frequency (f) that is measured in Hertz (Hz) or cycles per second, whilst the variation in space is regarded as the wave length (λ). These two factors are interrelated due to the speed of the sound.

Therefore:

$$V = f\lambda \qquad (3.1)$$

Where

V = speed of sound
f = frequency in Hertz
λ = wave length

For instance the musical scale, the frequency (f) of the middle c = 256 Hz, and it's wave length (λ) is about 1.34 m. Infact, the wave length is the most important character of a sound wave, as far as the calculations regarding the sound radiation are concerned.

Most of the sounds of the real life are not harmonic ones. Usually, the sounds from a musical instrument consist of a base note upon which superimposed a series of higher harmonics that have series of higher harmonic frequencies, usually are multiples of base frequency. Of the traffic noise, E.g. the noise radiating from the gear boxes of motor vehicles is often of a similar nature, but usually with much higher harmonics and it includes sounds that contain a random and a variable mixture of many frequencies. Such sounds can be described as noise. When there is a uniform spread of sound energy over all frequencies, the sound can be called the "white noise" somewhat similar to the white light that contains a colour spectrum. The "Pink noise" is more unifrom over all frequencies. Therefore the distribution of the sound energy is a function of it's frequency, and can be called the noise spectrum.

The magnitude of the sound pressure at the threshold of ear pain is about 107 times greater than the pressure associated with the softest sound we normally hear. As the ear does not appear to respond to pressure changes in a linear way, to avoid using the larger numbers such as 10^7, a logarithmic scale is used. Sound is measured using the term known as sound pressure level (SPL), and is defined as;

$$\frac{SPL}{20} = \log \frac{\text{RMS of pressure fluctuation}}{\text{Reference value } (20\mu pa)} \qquad (3.2)$$

(Turner and Pretlove, 1991)

Where

RMS = Root mean square value of fluctuations

The reference value 20 micro Pascal (20 μPa) = Sound pressure level of 1 kHz sound just audible by healthy young ears. It is given by a zero value at decibel scale.

For the sounds other than those of extremely high intensity, the acoustic waveform is preserved as the wave is spread out. Therefore, it is convenient to consider sounds as a superposition of harmonic components of different frequencies. An analysis to the measured sound in this manner can be made by simple frequency filtering in narrow or broad bands. Broad octave bands are often used in simple noise measurements. The octave band spectrum can be found by averaging the narrow band spectrum over the intervals of one octave. An octave interval spans from a lower frequency upto twice of that frequency. The nomenclature of the octave is derived from the musical scale. e.g. the 500 Hz octave band starts at 356.6 Hz and extends upto 707.2 Hz. Figure 3.1 shows the narrow band spectrum and the corresponding octave band spectrum.

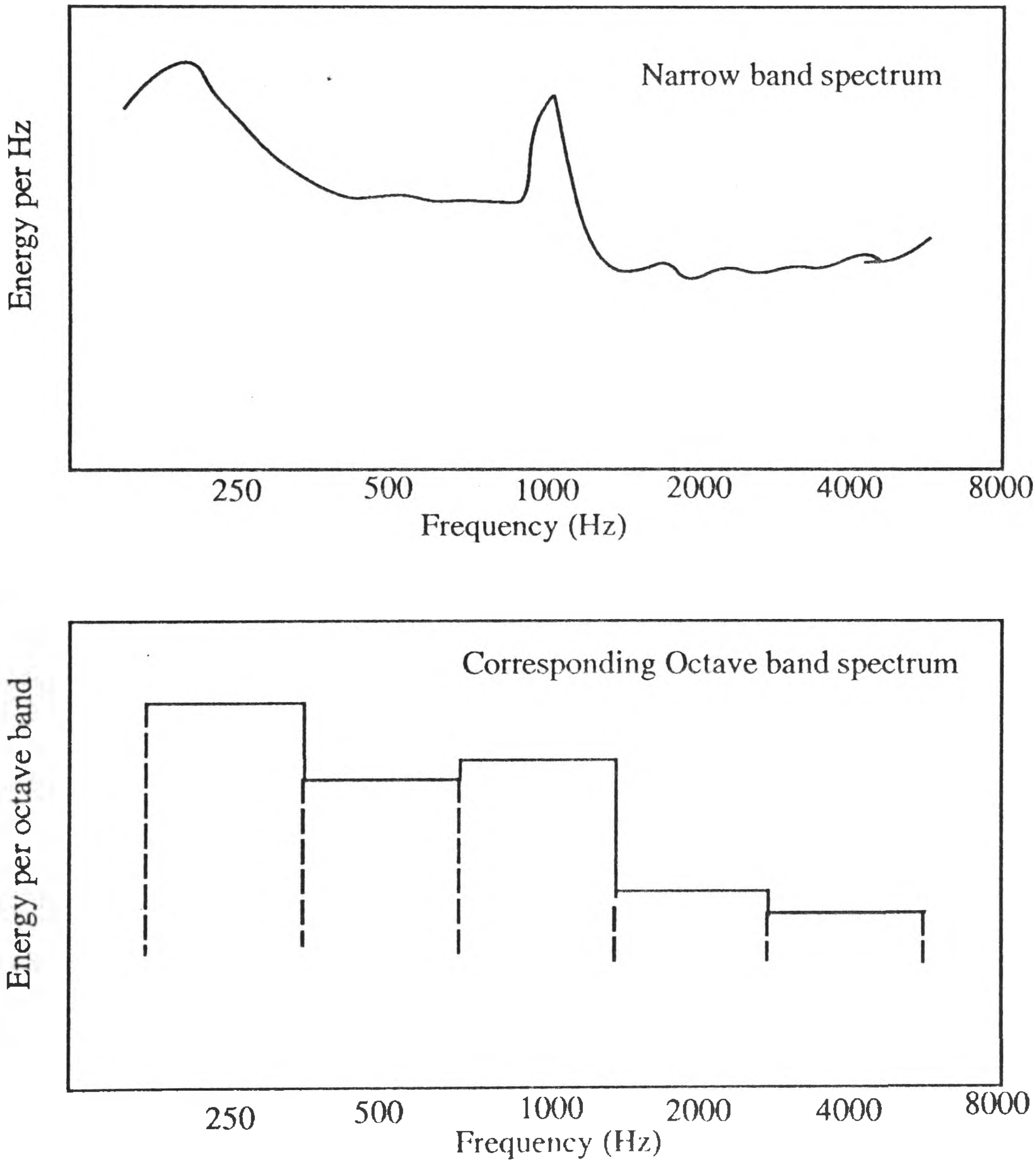


Figure 3.1 Narrow band spectrum and corresponding octave band spectrum (After Turner and Pretlove, 1991)

The narrow band spectrum for a harmonic sound consists of a single vertical line at the relevant frequency. The energy spectrum is very characteristic of a noise, and very distinctive. The human ear can make sort of distinctions with a great sensitivity, it can easily differentiate the same note played by a violin and a piano separately, or at a more sensitive level a speaker can be identified even on the telephone.

The narrow band spectrum may be essential for problem diagnosis since the great amount of detail it displays. But, the broad octave band spectrum is often used in simple measurements since it is quick and provides an adequate description of the noise (Turner and Pretlove, 1991).

3.2.2 Sound Transmission in Air

There are three effects of the sound that tend to reduce the intensity of the sound comparative to the calculations of the inverse square law.

- sound absorption by air itself
- sound refraction away from the ground due to the action of the wind speed
- sound refraction away from the ground due to the action of the temperature.

Eventhough the sound absorbed by air causes the intensity of the sound to be reduced, under some conditions, the ingredients of wind and the temperature do raise the sound intensity. Comparatively, the sound absorption quality in air is less significant in traffic noise control purposes because, the absorption value in air is calculated as dB per 100 meters (Turner and Pretlove, 1991).

In the passage of sound wave the compression of air is so rapid in the passage of the sound wave compression. Therefore the adiabatic gas law can be applied for that.

$$PV^{\beta} = C \qquad (3.3)$$

where

P = Atmospheric pressure

V = Volume

C = constant

$\beta = 1.4$

As there are perturbations of both the pressure and volume about fixed static values, this can be expressed as;

$$P = P_0 + \delta P$$

$V = V_0 - \delta V$ (taking sign convention into account for gas as minus where as it is plus for a solid)

where

P_0 = Atmospheric pressure

V_0 = Volume of air subjected to compression

δP = Acoustic perturbation corresponding to acoustic perturbation σ in the analysis of a solid bar.

P = Total pressure cause due to wave compression

V = Total volume created

By differentiation of the adiabatic equation:

$$\delta P V_0^{\beta} - P_0 \beta V_0^{\beta-1} \delta V = 0$$

or

$$\delta P = P_0 \beta \left[\delta V / V_0 \right]. \qquad (3.4)$$

This is the Hook's Law for air, and therefore the Young's modulus is;

$$E_{air} = P_0 \beta \qquad (3.5)$$

In comparison to the application of the Hook's Law to a solid bar, this can be given as;

$$C = \sqrt{\left(P_0 \beta / r\right)} \text{ or } C = \sqrt{(\beta RT)} \qquad (3.6)$$

where

R = Gas constant

T = Absolute Temperature

ρ = Density of air

Therefore, the conclusion drawn from this is, that 'C' depends on absolute temperature 'T,' and the elastic modulus also can be expressed as;

$$P_0 \beta = \rho c^2 \qquad (3.7)$$

where

c = speed of sound in air

when the speed of the sound is calculated,

where

ρ = 1.18 Kg / m^3

β = 1.4

$P_o = 10^5 N/m^2$;

$$c = \sqrt{\left(P_o \beta / \rho\right)} = 344 \text{ m/s (for air)}$$

According to the above analysis, it can be concluded that the speed of sound is the same for all the wave lengths, and therefore, the distortion of the sound due to dispersion will not occur. Sound in a given gas (in which R is constant), such as the atmospheric air, travels solely at a speed that is depended upon the square root of the absolute temperature. Accordingly, the sound waves also are refracted or bent when travels from one medium to another, as happens with the nature of the light waves. Sound mirages (same occurrence as in light), may be formed as a result of this bending, under some meteorological conditions. The wind and it's ingredients can also be influenced by the concentration and dilution of sounds in the air (Turner and Pretlove, 1991).

Sound transmission in different mediums varies from each other. Characteristics of sound depending on the medium of transmission, Young's modulus, density, wave velocity and the characteristic impedance is given in table 3.1.

Table 3.1 Acoustic properties for different materials. (After Pretlove, 1991)

Material	Young's modulus	Density kg/m^3	Wave velocity m/s	Characteristic impedance NS/m^3
Concrete	$3 X 10^{10}$	2400	3500	$8.4 X 10^6$
Hardwood	$1 X 10^{10}$	600	4000	$2.4 X 10^6$
Glass	$6 X 10^{10}$	2400	5000	$1.2 X 10^7$
Aluminium	$6.9 X 10^{10}$	2720	5030	$1.4 X 10^7$
Steel	$2.1 X 10^{11}$	7800	5200	$4.1 X 10^7$
Air	$1.4 X 10^5$	1.2	340	$4.07 X 10^2$
Water	$2.3 X 10^5$	1000	1500	$1.5 X 10^6$

Sound is dissipated by distance and as it spreads in all directions from the source, it's pressure will decrease according to the inverse square law, as the area to be influenced is increased. The effect of sound attenuation (decrease) is dominated by the spreading effect for the distances under 300 meters. The radiating sound waves from traffic usually take about 2-3 meters to settle down to a well defined periodic form, and a proper attenuation occurs within a distance of 10 meters. Different sound frequencies are affected differently, as the higher frequencies are more rapidly attenuated. At long distances all sounds are changed to a rumble.

Due to the typical temperature inversion prevailing during night times, the horizontally spreading sound waves are bent downwards whilst travelling, and these factors can overcome the normal line- of-sight shielding (Bryant, 1975).

3.3 LOUDNESS

The loudness depends on the sound pressure level and the frequency. Eventhough there are several curves which have been developed to show the equal loudness, most of them are valid only for certain test conditions. But the Fletcher-Munson Curves as per Figure 3.2 below [International Standards Organisation (ISO), 1975], are frequently used to show the loudness data. The data for Fletcher-Munson Curves have been obtained under the test conditions provided;

- o the source of noise is directly ahead of the receiver.
- o the noise reaches the receiver in a form of free progressive plane wave such that the receiver is in it's free field.
- o the sound pressure level is measured in the absence of the listener.
- o both ears are used under test conditions.
- o test receivers are in the age group of 18 to 25 years with normal hearing ability.

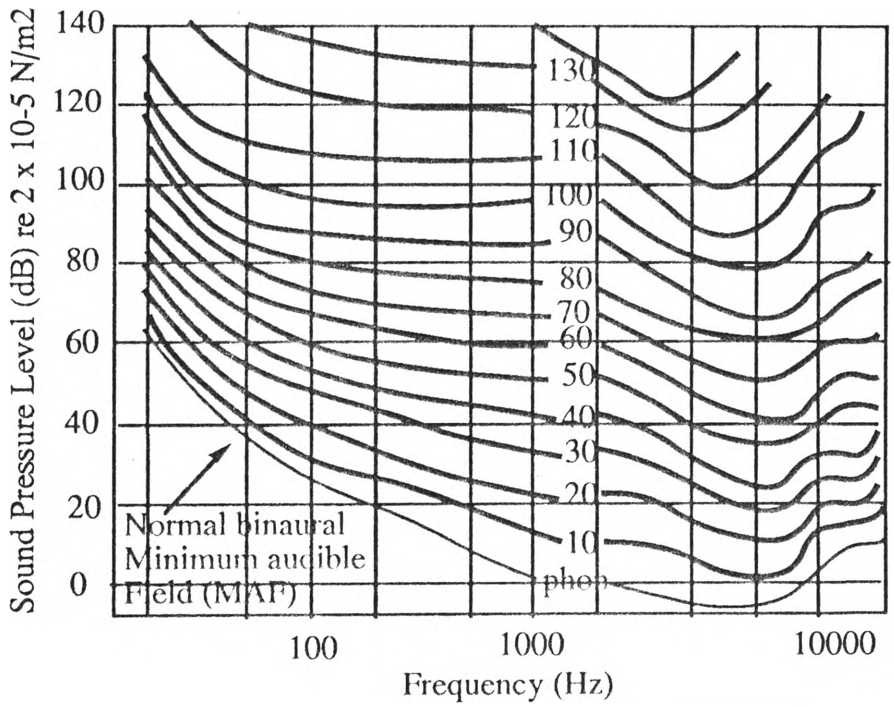


Figure 3.2 Fletcher - Munson Equal Loudness Contours. (After Bruel & Kjaer, 1977)

The sound pressure of the reference tone is 2×10^{-5} N/m^2 and it defines the zero point on a loudness scale. The unit of perceived loudness is measured with the unit called 'phon'. The reference sound pressure ($2x10^{-5}$ N/m^2), also defines the 0 dB point on the vertical axis. The ear's sensitivity varies for frequencies other than 1 kHz level. This effect is shown in Figure 3.2, and only at the reference frequency, the loudness of a sound in phon equals to SPL in dB.

In Fletcher - Munson Curves, a reference tone is played for test to be judged by the receiver, who has the task of adjusting the amplitude of an alternatively heard 1 kHz reference tone, until it has the same perceived loudness. It is traditional to use Decibels in terms of sound intensity. Due to the fact that intensity is the power transmitted per area and is proportional to the square of the sound pressure. Therefore relative sound intensity is seen to be equivalent to sound pressure level. Table 3.2 shows that the relationship of the measured, pressure level of a sound to it's apparent loudness as perceived by an average listener.

Table 3.2 Relationship between loudness, sound pressure, and Decibels. (After Samuels, 1977)

Site	Apparent Loudness	Sound pressure level(μpa)	Sound pressure level(dB)
Quiet street or road	very faint	20	0
	just audible	-	10
	rustling leaves	200	20 log200/20=20
	private office	2000	20 log2000/20=40
	suburban bedroom	2000	20 log2000/20=40
Busy street or road	average office	20,000	20 log3=60
	noisy office/car	200,000	20 log4=80
	loud horn of a car	20,000,000	20 log6=120

A reduction of noise by 10 dB is subjectively considered as equivalent to halving the sound level. The sound pressure level drops by 4-6 dB for each doubling of distance away from the sound source.

$$\text{Relative sound intensity} = 10 \log \frac{\text{Intensity}}{\text{Reference Intensity}} \text{ dB} \quad (3.8)$$

where

intensity is the power transmitted per area and is proportional to the square of the sound pressure. Accordingly, the relative sound intensity is seem to be equivalent to sound pressure level (Lay, 1986). This effect is illustrated in Table 3.3.

Table 3.3 Relationship between sound pressure and intensity (After Young, 1988)

Intensity (W/m^2)	Example	Sound Pressure Level (dB)
10^2	Jet engine, gun shot	140
10^1	Threshold of pain	130
10^{-1}	Car horn at 1 meter distance	110
10^{-2}	Discomfort/ hearing damage	100
10^{-3}	Inside an underground train	90
10^{-4}	Inside a bus	80
10^{-5}	City traffic at peak hour	70
10^{-6}	Busy department store/ hotel	60
10^{-7}	Quiet car average office	50
10^{-8}	Quiet living room	40
10^{-9}	Library	30
10^{-10}	Bed room at night	20
10^{-11}	A dropping pin	10
10^{-12}	Threshold of hearing	0

3.4 DECIBEL (dB) SCALE

Human ear responds to various sound frequencies in an uneven fashion, in that it does not respond to linearly to sound. It responds according to a logarithmic scale (repeated doubling of sound intensity is perceived with the repeated addition of constant amount).

3.4.1 Weighting Factors and dB(A) Scale

Most of the sound measuring instruments are provided with built in electronic filters with a frequency response. These are approximately equal to the loudness curves of Figure 3.1. Different filters such as A, B, C, and D are being used for different sound pressure levels. The "A" weighting scale is used for more common noises due to the simple use of it, and as those readings are well correlated with perceived loudness. Sound with this weighting usually measured by electronic filters within measuring instruments is designated by dB(A). Change in dB(A) is well correlated with subjective changes. In this study the road traffic noise level in dB(A), will be measured by a sound level meter using an A-weighting network.

The noise level exceeding the prescribed limit for x per cent of the time will be denoted by Lx. The most common noise exceeding level that will be used is L_{10}, which is the noise level exceeded for 10% of time. Accordingly, L_{50} is the noise level exceeded for 50% of time, and L_{90} is the noise level exceeded for 90% of time.

3.4.2 L_{10}(18h) Scale

The daily exposure to traffic noise will be described by the measure called L_{10}(18h), which will be calculated by averaging the L_{10} s for each of the 18 hour test survey period between 6 am and the midnight (18 hour), and the value calculated over this L_{10}(18h) has been found to provide better indication of the annoyance due to road traffic noise to the nearby residents than from the values for 24 hours period. L_{10}(18h) is the maximum noise level in dB(A) exceeded for 10% of the time between 0600 hours and 2400 hours (these 0.1x18=1.8 hours need not to be continuous). The L_{10} values for a 3 hour period, L_{10}(3h) is about 1 dB(A) greater.

3.4.3 L_{eq} scale - Equivalent Continuous Sound Level

An alternative single number measure of the fluctuating noise levels caused by a stream of traffic is the continuous sound level will be denoted as L_{eq}. This sound level is steady, and during the measurement period, it would carry the same energy as the time varying signal, and it is measured in terms of a weighted energy level perceived over a given or measured period. This L_{eq} is often used to estimate the community noise levels. Research had shown good relationships between L_{10} and Leq (Brown 1980).

$$10\ L_{eq}/10 = \text{Mean of } 10\ \text{dB(A)}/10 \tag{3.9}$$

By utilising the local urban data, Burgess (1977) and Saunders and Jameson (1978) suggested that:

$$L_{10} = L_{eq} + 3 \tag{3.10}$$

3.5 NOISE RATING (NR)

The noise rating is determined by the point on it's spectrum that is highest relative to the NR curves. These NR curves specify the maximum sound pressure levels permissible in each octave band and take the form of a family of curves derived from the equal loudness as per Figure 3.3. Eventhough a noise criterion (NC) types of curves also have been developed to serve the same phenomenon, they have been found less beneficial over higher ranges of spectrum and loudness, such as proved by the NR curves.

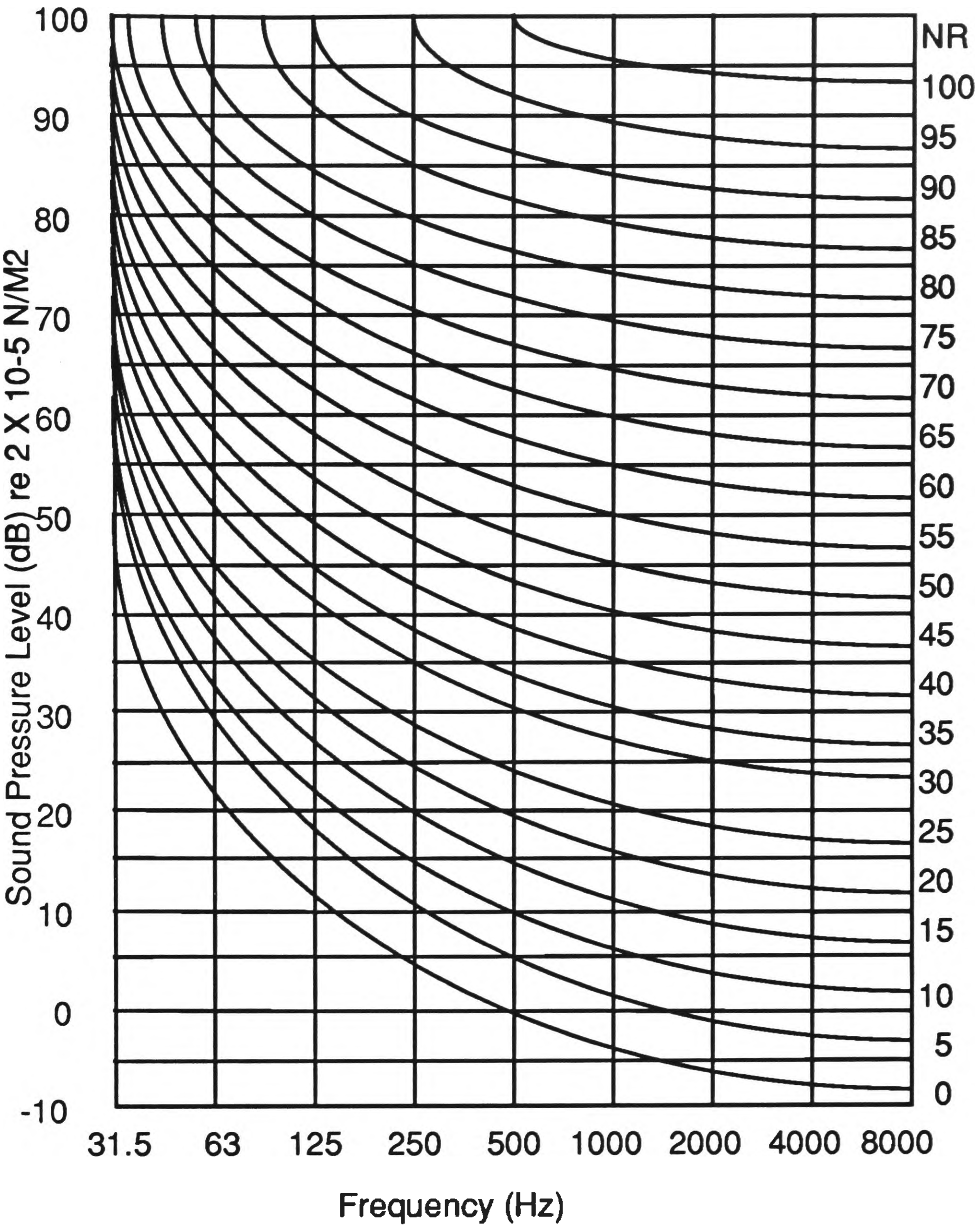


Figure 3.3 NR Curves. (After Bruel & Kjaer, 1978)

3.6 ADDITION OF DIFFERENT SOUND PRESSURE LEVELS

When there are two or more sources of noise available (traffic noise level at an intersection of a road), and it is known that the contribution of each road individually to noise level, the following rule is being used to add them together, provided that the sources are not correlated, it is fairly obvious that the energies will have to be added. But when noises do arise from a common source, they may be well correlated, and the energies will not be added directly. Accordingly, the calculation of sound intensity of many sources is a tedious process. However it can easily be done by using a "nomogram" (Ref: figure 3.4).

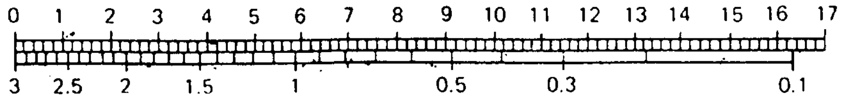


Figure 3.4 Application of a nomogram (After Turener and Pretlove, 1991)

3.6.1 Using a Nomogram for the Summation of Noise Levels

When the traffic noise is measured in octave bands the overall noise levels can be found by using the nomogram method. For example if the overall noise measurement is 74.2 dB, the nomogram method can be used to check whether the sums of octave band values do give the same overall sound pressure level (Turner and Pretlove, 1991). Table 3.4 shows comparative noise levels relevant to different octave band frequencies.

Table 3.4 Comparative noise levels relevant to different octave band frequencies.

Octave band Frequency (Hz)	Sound Pressure Level [dB(A)]
100	70
225	71
480	64
1000	69
1800	65
4200	64
7900	52

Figure 3.5 shows the method of addition of noise levels for the use of nomogram method as described below.

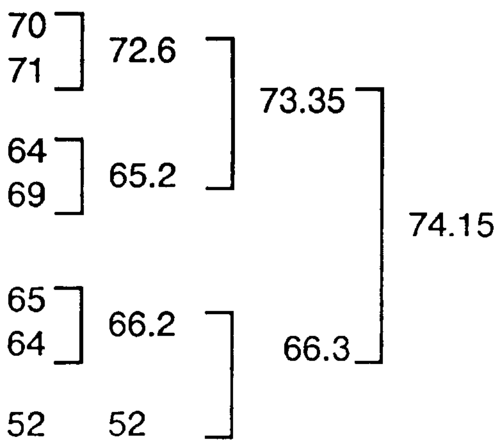


Figure 3.5 Addition of decibels using the nomogram method

When using the nomogram, the lower value of the first two noise level values (the first two entries of the table) to be subtracted from the higher value. Here, the difference is only 1dB, and the corresponding value to this to be checked along the upper scale of the nomogram. The corresponding value addition is to be made accordingly, and here it is 2.6 dB (to nearest 0.1 dB, to opposite direction on the nomogram). Therefore, the sum is; 70 + 2.6 = 72.6 dB. Accordingly, the calculations to be made from left to right adding the pairs of values as per Figure 3.5. This result is almost close to the measured values, and hence, it can be regarded as satisfactory.

3.7 COMMUNITY NOISE ANNOYANCE

This is a combination of both the domestic and industrial (including traffic) noise. The nuisance caused by community noise is considered as a function of loudness, and is measured in dB(A). These are some other factors such as psychological factors to be taken into account. The community noise is to be measured for the purpose to assess the working efficiency, social privacy, and personal tranquillity, and the health.

Community noise levels are simply taken in dB(A), and are compared with a set criterion, in-order to check whether the measured levels do exceed the set levels. If it is required to mitigate these noise levels, further noise measurements have to be taken in octave bands, and be compared with the NR curves. These NR curves do enable the frequency bands containing the problem to be identified, and accordingly, appropriate noise control measures can be taken.

The community noise levels measured in dB(A) are corrected by adding a correction factor to convert it to an equivalent steady noise level, as follows.

- In case if the noise contains impulsive peaks, by adding 5 dB to the average peak levels.
- In case if a pure tone is perceptible, by adding 5 dB(A)

3.8 NOISE LEVELS RELATED TO HEARING DAMAGES

The workmen in the heavy industries are usually subjected to hearing impairment due to the continuous heavy noise levels that occur throughout their life. In a similar manner, the occupants of the houses located close to the urban roads too may be subjected to the same type of hearing impairments. For example occupants subjected to noise levels of about 85-90 dB(A) for about an 8 hour duration a day, has a chance of loosing their hearing ability by 50 dB or sometimes will have to suffer total deafness. If the normal noise level is increased by further 3 dB(A) e.g. 93 dB(A) and the duration is reduced to 4 hours a day, the harm caused is similar to that of a noise level of 90 dB(A) that prevails for 8 hours (Turner and Pretlove, 1991).

3.9 MEASUREMENT OF INTERFERENCE TO SPEECH DUE TO NOISE

Most of the human activities depend upon the verbal communication, either as direct face-to-face conversation or by telephone or over the media equipment such as radio or television. Consonant of the normal frequency has a power of about 0.3 μW, and the shouting will increase it even upto 2 mW. The normal speech is carried by high frequency, low energy consonants. If the noise contains a high frequency such as 500 Hz and above, it has a higher masking effect. The main frequency band for speech and hearing is about 500 Hz to 4 kHz, and speech levels can vary from a whisper to a loud shouting. The distance between the source of the sound (or noise) and the receiver (listener) is also an important factor. Low frequency background sound is more acceptable than the high frequency sound (noise) (Health and Safety Executive, 1990).

In some countries, Speech Interference Levels (SIL) are set. SIL is called the average sound pressure level (SPL) in three octave bands centred at 500 Hz, 1 kHz, and 2 kHz consecutively. Higher SIL values can be tolerated when the distance from the source to the receiver is large (Fig. 3.6) (Health and Safety Executive, 1990).

When the SIL value of the background noise is higher, people usually increase the intensity of their voice to match with it. It can be shown that if the SIL levels inside a visitor lounge of a residential house located near an arterial road is 50 dB(A), the speaker has to use a raised voice to communicate with somebody (receiver) in the same house who is at 6 meters away, and has to use a very loud voice, if the receiver is at a point 12 meters away. Figure 3.6 shows the maximum SIL values for uninterrupted speech. Table 3.5 shos the measured SIL levels.

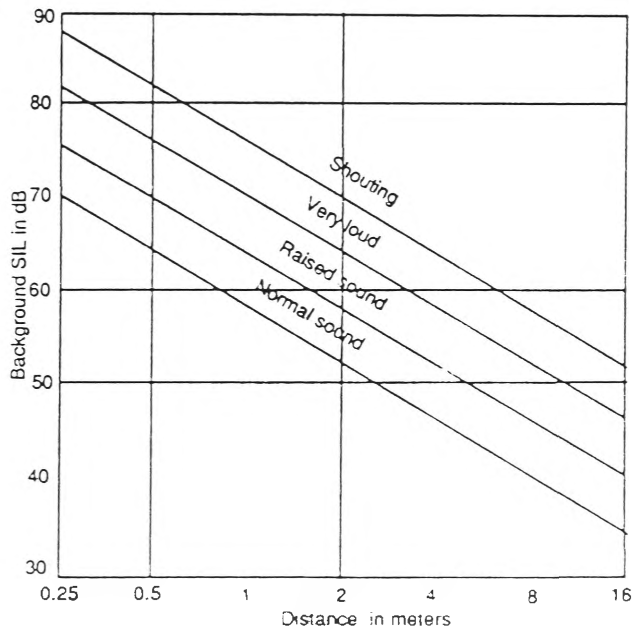


Figure 3.6 Maximum background SIL values for uninterrupted speech. (After Hassall and Zaveri, 1988).

Table 3.5 Measured SIL values (After Hasall and Zaveri, 1988)

Voice Level	Normal	Raised	Very Loud	Shouting
SIL	40	55	72	85

In some cases, the dB(A) values are used in place of SIL values for convenience.

$$dB(A) = SIL + 9 \quad \text{(male)} \tag{3.11}$$

$$dB(A) = SIL + 14 \text{ (Female)} \tag{3.12}$$

(After Hassall and Zaveri, 1988)

3.10 OTHER MEASUREMENT INDICATORS

In addition to the above mentioned noise related indicators, there are some more measuring indices in use. Traffic noise Index, noise pollution level, and the day and night level L_{dn}, which are obtained by applying different weighting factors to the noise levels measured during different periods of a day, are some of them.

3.11 ACCEPTABLE NOISE LEVELS

The acceptable noise levels for different areas and times of the day have been shown in Australian Standard AS 1055 (1973). These levels were not designed to assess the acceptability of road traffic noise, but they can be used to make an assessment of the noise levels.

Lawrence and Burgess (1977) found that the acceptable level for for a residential zone in Sydney was exceeded by 15 dB(A) more than the predicted acceptable levels. The acceptable noise levels as per RTA regulations are 63 dB(A) maximum for day time, and 45 dB(A) maximum for night time (internal), and 55 dB(A) maximum for night time (external).

Studies carried out in UK have attempted to relate the dissatisfaction of the residents exposed to the traffic noise, with L_{10} (18 hour) measurement of the noise. Langden (1976), has concluded that the point at which the dissatisfaction begins to outweigh the satisfaction is about 66 dB(A) for L_{10} (18h). The level specified by UK noise regulations is 68 dB(A) for L_{10} (18h). The land compensation act of UK (1973) requires compensation or remedial work to be done if L_{10} exceeds 68 dB(A), measured at a distance of one meter, in front of a residential building facade. This act, however, applies to new and diverted roads but not to existing roads. The cost estimated for the required remedial work and compensations in UK were Pound Sterlings 250 million per annum that is a cost attributable to road users.

Eventhough the adopted external noise level for housing facades (L_{10} values) was 68 dB(A), in the UK and Australia it has been argued that the maximum acceptable values of noise (L_{10}) inside a house should not be exceeded for more than the following limits.

	Day	Night
Country areas (day time)................................	....40 dB(A),	30 dB(A)
Suburban areas (day time)...............................	....45 dB(A),	35 dB(A)
Busy urban areas (day time)................................	50 dB(A),	35 dB(A)

(After Ouvy, 1976)

When 10 dB(A) is allowed for attenuation from the surrounding, the maximum external values for the above areas would be about 50, 55, and 60 dB(A) consecutively. During the summer season, under the windows open condition, the above criterion would not be achieved, and hence, the acceptable external noise level would be around 55 dB(A).

Acceptable noise levels for the residential areas were clarified in AS 1055 (1978), as acceptable range of noise values within the range of 50-60 dB(A). Similar standards were allowed in UK- 68 dB(A), and in New Jersey as well, and not exceeding the standards set aside by United States Environment Pollution Authority (USEPA) and Australian Road Research Board (ARRB) (Schubert, 1990). At Wollongong Central Business District (CBD) area too, the values measured at different sites have been generally higher than by 10 to 15 dB(A) the acceptable values of AS standards (as per field surveys of the author). Noise levels, about 15 dB(A) higher than the AS standards have been recorded in Sydney as well.

Analysis of the data collected by Brown (1978), at south-east freeway of Brisbane have shown that L_{10} (18h) free field levels of less than 60 dB(A) would generally be regarded as acceptable.

Stationary noise levels prescribed for cars, motor cycles, and the trucks do differ from each other. Eventhough the prescribed maximum noise level for the trucks manufactured after 1983 is 94.5 dB(A), and 84 dB(A) for the cars manufactured after 1982, more stringent goals would be driven by results of this research.

3.12 NOISE CONTROL REGULATIONS

Legislation in New South Wales of Australia, differentiates between "occupational" and "environmental" noise. The noise in factories and the other occupational situations, affecting the workers in their working environment, is covered by the factories, shops and industries Act, which is administered by the Department of Industrial Relations and Energy.

The noise control act (1975) of New South Wales had given the powers to State Pollution Control Commission to take appropriate action to safeguard the members of the community from transport , industrial and commercial noise issues.

Noise from a machine such as an air conditioner or a filter fitted to a swimming pool can be measured by using a sound level meter, and the required engineering control measured can be set by legal noise. Such requirements could indicate the fitting of a sound proof enclosure or a limitation on the times of use.

Provision is made for quantative standards to be set for the maximum levels of noise permitted from the machinery and motor vehicles. The maximum permissible noise levels may also be specified for individual premises scheduled under the Act, having regard for aspects peculiar to the premises, such as the insulation provided by the walls, buildings and other physical features, the size of the site, and it's location in relation to other developments.

On the other hand, many of the major causes of noise problems associated with a neighbourhood, such as parties, band practice and barking dogs are not capable of quantification. The responses of noise to neighbourhood noise are subjected to many variables, such as the time it is made, it's location and the attitude of the person or persons subjected to noise.

The Act recognises that the adoption of a quantative approach to noise problems, similar to that adopted in relation to the control of air and water pollution, but those would be impracticable in many cases. As an alternative to a quantative approach in those areas where standards cannot be set, the Act has adopted the qualitative test of "offensive noise." "Offensive noise" is defined as noise that, by reason of it's level, nature, character or quality, or time at which it is made, or any other circumstances, it is likely to harm, offend or interfere unreasonably with people's comfort or repose. Through this approach, the State Pollution Control Commission, local councils, the maritime service board, the police and the courts can apply the necessary controls in an effective and equitable manner.

The Act provides for the making of the regulations covering a wide range of matters, including the prevention or control of regulations relevant to noise made by animals on any premises. It's operation is based on five fundamental controls;

- o Scheduling and licensing of premises and control over noise from these premises.
- o Pohibition of sale of noisy articles.
- o Issuing of noise control notices.
- o Issuing of noise abatement orders.
- o Issuing of noise abatement directions.

The design rule criterion for noise emissions from the new vehicles was published by the Federal department of transport in 1972, and a revised design rule reducing the maximum permissible traffic noise levels were published in 1976. Regulations setting criteria for the in-service vehicles were prepared by the Environment Protection Authority of Victoria in 1976 (Snow and Law, 1978). Before 1972, the legislative control on motor vehicle noise in Australia relied on the assessment of vehicle noise by police officers or the officers of registering authorities.

3.12.1 New Traffic Noise Regulations

In 1971, vehicle manufacturers were concerned at rather ad-hoc nature of the existing subjective assessment of vehicle noise by that time. They have requested that an Australian Design Rule (ADR 28, 1976), be drafted incorporating objective test procedures, and criteria for noise emissions from motor vehicles. Draft design rules were forwarded by the Advisory Committee for Safety in Vehicle Design (ACSVD) to the Motor Transport Group (MTG) for consideration, which in-turn had forwarded the finalised draft to the Australian Transport Advisory Council (ATAC) for endorsement. The ATAC consists of the Federal Minister of Transport and six other State Ministers for Transport.

The vehicle manufacturers have submitted the design rule test data to the Federal department of Transport for review. The department then had made the recommendation to the Australian Motor Vehicle certification Board (AMVCB), based on the test data, and once the AMVCB has endorsed a recommendation, compliance plates are issued to the manufacturers for the particular model concerned. Accordingly, the registering authorities are able to check the vehicles for the compliance of the design rule requirement.

The first design rule related to the motor vehicle noise was ADR 28, which uses a test procedure contained in European Economic Commission-Regulation 9. As it had been regarded as unsatisfactory, the ATAC requested the ACSVD to review the design rule, paying attention to both the test method and the schedule of maximum permissible noise levels. The committee was augmented to include persons with a background in acoustics and the representatives of the state environmental control authorities.

A test programme regarding the motor vehicle noise levels were carried out, and a new Design Rule had been introduced (ADR 28 A), in 1976. ADR 28 had been endorsed by ATAC. Due to protests by the industry within the ACSVD, the implementation of this rule too had been deferred indefinitely.

The Australian Environmental Committee (AEC) was formed in 1977, supported by a standing committee composed of the Federal and state administrative heads of the relevant departments, and advised by the Motor Vehicle Emissions and Noise Standards Advisory Committee (VENSAC). A joint committee was formed by bridging the standing committee of AEC and the MTG of ATAC in 1978, with the idea of advancing towards the mitigation of traffic noise emissions.

3.12.2 Noise Control Regulations for In-Service Vehicles

Eventhough, the vehicle noise control was traditionally left to the law enforcement officers to determine the harmfulness of the traffic noise, these subjective provisions were placed by the technical provisions, and they do specify the maximum permissible noise levels for various classes of motor vehicles together with the test procedures. ADR 39 had been introduced in 1985.

The first, in - service vehicle noise regulations were introduced in Victoria in 1976 by the Environmental Protection Authority (EPA) (Snow and Law, 1978) and they have been updated since then. These regulations were considered for the formation of vehicle noise control regulations in New South Wales and in Tasmania.

The maximum noise levels have been decided for the available data of in - service vehicle noise levels. In New South Wales too, some similar traffic surveys had been carried out which involved about 1200 passenger cars, 1200 trucks and buses, and about 500 motor cycles.

Eventhough, the in - service noise regulations were introduced in New South Wales in 1979, it is interesting to note that the test levels have been floated since then, and only a limited percentage of post ADR 28 standard vehicles will fail the test.

It had been suggested that the prescribed 95 dB(A) noise test level allowed at 7.5 meters according to Victorian standard, is too high for the trucks. The test method used for heavy diesel engined vehicles is identical to USEPA levels, for heavy interstate transport vehicles of more than 45 Tons. Measurement is done at 50 feet (15.24 meters) instead of standard 7.5 Meters distance used in Victoria, and this test method was first devised by the Department of Environment (DoE), in UK. The maximum permissible noise levels prescribed by EPA was higher than the maximum levels of USEPA and DOE regulations for the diesel engined trucks.

The maximum permissible noise levels, at 15.24 meters distance away from the centre of the road, set for the truck, by the USEPA of the United States, in 1977 was 80 dB(A), irrespective of the speed limit travelled. To comply with the regulations of EEC, it had been endeavoured to reduce these noise levels to 87 dB(A). Eventhough, there was a draft by the Standards Association of Australia to reduce the vehicle noise emissions in three stages (AS.No.75075); as the maximum permissible noise levels for trucks at 7.5 Meters as 92 dB(A) for stage one, 85 dB(A) for stage two, and as 80 dB(A) for stage three, these levels were removed before the final drafting had been done.

Implementations of traffic noise regulations require a road patrol vehicle equipped with noise testing equipment, and inspectors trained to measure noise levels. This road patrol team will have the directions to take the actions against the modified or defective exhaust systems. In addition, the police already has authority under the motor Traffic act, to control noise from motor vehicles. Accordingly, thousands of vehicles are stopped every year by the police, who rely upon the subjective assessment of whether the noise is "undue" or "avoidable." Such assessment can detect only the most offensive cases of motor vehicle noise.

3.13 VEHICLE EMISSIONS AND NOISE STANDARDS ADVISORY COMMITTEE

The Vehicle and Noise Standards Advisory Committee (VENSAC), had been established under the auspices of the Australian Environmental Council to investigate emissions from motor vehicles. One of it's task is to review existing State and Commonwealth legislation and procedures with the objective of developing uniform procedures for both pre-registration and in-service noise tests for each category of motor vehicles.

VENSAC has agreed for the in-service motor vehicle noise control in Australia, on a technical basis. The committee recommendations specify the test procedures and maximum permissible noise levels for the following classes of motor vehicles:

- o Passenger cars, passenger car derivatives and multi purpose passenger cars.
- o Diesel engined trucks and buses.

- Petrol and LPG engined trucks and buses.
- Motorcycles.

3.13.1 Motor Cars

The State Pollution Control Commission has approved a regulation under the noise control Act to prescribe a maximum noise level for all motor cars in New South Wales. This level and the specified test method are sparingly the same as those recommended by VENSAC, but there are some differences in the measurement procedure to allow road side testing in New South Wales. In Victoria, on the other hand, motorists are required to take their vehicle to a central testing site for inspection.

Under the above regulation, the officers of the State Pollution Control Commission, may stop the vehicles for testing or serve notices on owners requiring presentation of vehicles for testing.

Cars are sometimes made noisier by the owners who modify their exhaust systems, E.g. fitting sporting mufflers. The draft regulation requires the owners to maintain the noise control equipment and absorbing material on their vehicle in good order, and makes it an offence to use the cars where such equipment is removed or replaced by equipment with inferior acoustic performance.

The draft regulation also provides for the commission to issue a notice requiring an owner to carry out specific work where offensive noise is being emitted from a motor vehicle. In extreme cases, the registration could be suspended.

3.13.2 Trucks

Measurements have been conducted on trucks to determine suitable procedures for in-service noise regulations. Owners of the vehicles suspected of emitting excessive noise may be required to take their vehicles available for testing at a noise testing station.

3.13.3 Standard and Trailer Type Motor Cycles

Measurements obtained from the off road recreational motor cycles, including mini and trail bikes, have been found to exceed those produced by registerable road motor cycles by amounts varying from 10-15 dB(A). Inadequate mufflers are shown to be the outstanding case.

In New South Wales, the vehicle noise regulations appeared to have suffered from an excess manipulation by the governmental committees at national level. Due to existing, uncontrollably increasing traffic noise levels which affects the human health, it is essential to introduce more stringent traffic noise control legislation as a measurement to mitigate traffic noise, at New South Wales, and the maximum permissible noise levels will have to be set, not so as to merely satisfy political considerations, but as to what percentage of the vehicle (specially, the heavy vehicle) population to fail the test would be acceptable. It is essential that the co-operation of the motor vehicle industry be obtained to implement the suggested levels of traffic noise controls.

3.14 AUSTRALIAN STANDARDS APPLICABLE TO TRAFFIC NOISE

There is a number of Australian Standards (AS) which are directly concerned with traffic noise and the noise reduction aspects. The most important ones with acoustic approach are considered in this thesis:

AS 1469-1983: Acoustic - Method for determination of noise rating number (NR), from the measured set of nine octave band sound pressure levels (31.5 Hz to 8 kHz) centre frequencies, according to AS 41, pertaining to the given noise environment.

AS 2702-1984: Acoustics - Specific methods for the measurement of road traffic noise and for the collection of associated data. This standard outlines also the minimum instrument requirements and preferred scales of measurements. Explanation is also given for the procedure for selection of measurements, sites and acoustic data that are to be recorded in-conjunction with acoustic measurements.

AS 3671- 1989: Acoustics- Road traffic noise intrusion, building sites and construction. In this standard, sets of guide-lines are provided for determining the acceptability of indoor and outdoor spaces, for specific activities in the presence of the traffic noise, and the extents of noise reduction or type of construction that might be needed to make such spaces acceptable. Also sets out the guide-lines for determining acoustical adequacies of existing buildings near routes carrying more than 2000 veh /day, are given.

3.15 MASKING EFFECT

Noises of the real life situations have the energies of many frequencies. Even when one note of a musical instrument is played, the output sound that is heard may contain additional frequencies that are harmonics. When a sound is heard, in presence of the back ground noise, the intelligibility of it depends upon the background noise level, and the frequency of it.

The masking effect is such that the human ear acts as though it is composed of a set of overlapping constant percentage of band width filters. The critical band width means that only the sound energy close to the frequency of the masked sound contributes significantly to the masking effect.

Critical band corresponds to a distance of about 1.3 meters along the basilar membrane of the human ear, and bears a direct relationship to the response maxima along it. The measurement of this critical distance is defined as "Bark." Over a wide range and high frequencies, the critical band width is about 23% of the centre frequency, or 1/3 of an "Octave Band," and from there, this effect is used as justification for the case of 1/3 octave band in noise measurement analysis, (Hassall and Zaveri, 1988) .

3.16 NOISE BARRIERS AND SCREENS

The use of sound barriers within the community is considered for special applications in severely affected areas such as schools, hospitals, and residential dwelling areas bordering the arterials. Capital cost data are summarised for several types of barrier construction. Although it may be relatively expensive, noise barriers do provide the only reasonable techniques for achieving substantial noise reductions in open areas of existing communities by actions taken beyond the right- of - way.

The noise barriers or screens are based on a placing of a physical obstruction between the source of the noise and the receiver. Eventhough the screens do help to mitigate the noise, a perfect attenuation cannot be achieved with them due to diffraction, and transmission of the sound through the them. But, for the solid noise barriers, the noise transmission becomes an insignificant factor. The noise observed at any point of it's field is composed of two parts namely direct sound, and the diffracted sound above the top of the screen.

The term " Noise Barriers" can be used in broad sense. Due to attenuation obtained from walls, earth berms, depressed configurations and the elevated configurations is dependent in all cases upon the same basic parameters such as line of sight distance, position distance, break in line of sight distance, and the subtended angle.

3.16.1 Noise Path From Source to Receiver

Figure 3.7 shows a section through a traffic noise barrier. Traffic noise emitted from the motor vehicles in the roadway can follow four different paths. First, the traffic noise takes a direct path to the receiver who can see the traffic well over the top of the barrier. As the barrier does not block their line of sight it provides no attenuation. Second, the noise follows a diffracted path to the receiver through the shadow zone of the barrier. The noise waves that pass just above the top edge of the barrier is diffracted (bent) downwards into the shadow zone shown in Figure 3.7. The larger the angle of diffraction, the more the barrier attenuates the noise in this shadow zone. The third is noise transmitted directly through the barrier into the shadow zone. This may be significant in some cases. For example, for more larger angles of diffraction, the diffracted noise may be less than the transmitted noise. In such a case, the the transmitted noise compromises the performance of the barrier. This effect can be reduced by constructing a heavier barrier. The last path of the noise is through the refracted path. After reflection the noise is of concern only to a receiver on the opposite side of the road across from the barrier. This effect can be reduced by providing acoustical absorption surfaces on the barrier face. However the treatment of this reflected noise does not give any benefit to the receiver who is in the shadow zone (NCHRP, 1976).

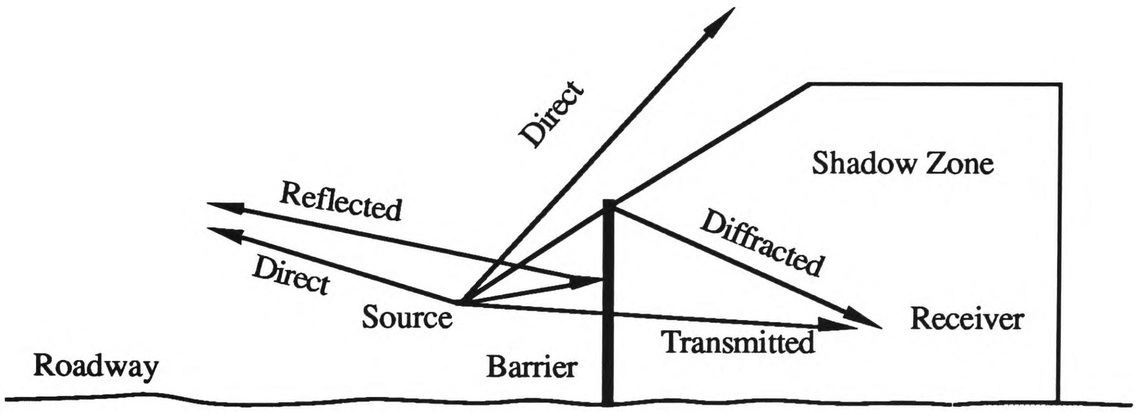


Figure 3.7 Noise path from roadway to receiver

Of the above mentioned four paths of the traffic noise, the noise is diffracted into the shadow zone is the most important parameter from the barrier design point of view. Generally, the attenuation obtained by a noise barrier represents only the amount sound energy diffracted into the shadow zone. In summary, when a receiver in the shadow zone hears the noise that has diffracted over the top of the barrier, and the resulting noise level is less than the level it would be without a barrier. Hence, the net benefit gained due to the presence of the barrier is called the "barrier attenuation".

3.16.2 Short Circuiting of Noise Around Edges of a Barrier

The highway noise act as a line source and hence a short circuiting of the path of noise transmission is possible. This is due to unshielded portion of the roadway where there is no barrier available. the receiver can see the roadway beyond the barrier when the barrier is not long enough. Then the noise pass around the ends of the barrier may short circuit the attenuation of the barrier. To achieve about 10 to 15 dB(A) generally, very long barriers are required. Therefore a barrier to be effective it should not only break the line of sight of the near-by section of the roadway, but also to to the roadway to the far end of the corridor. Figure 3.8 shows the short circuit path of the noise which reduces effectiveness of barriers.

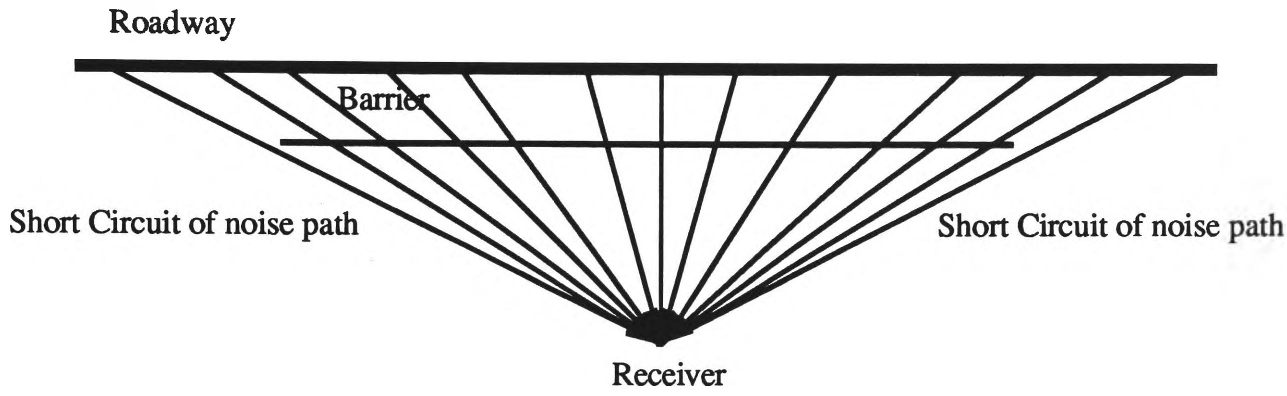


Figure 3.8 Short circuiting of noise around edges of a barrier (After Bolt, 1976)

When the observer is at a point protected by a noise barrier, the direct sound becomes zero. But, the diffracted sound depends upon the ratio of the effective height of the barrier, to the wave length of the sound. Here, the attenuation is directly proportional to the height in wave lengths. If the perceived sound at a receiver is weak, that means the barrier is achieving it's objective, but when the effective height of the barrier is small compared to the wave length, then the barrier becomes ineffective. When the barrier is a solid one, the direct transmission is close to zero. For material such as fabrics or thin tree shrubs, which do not provide any effects of sound screens, the above condition is not true.

3.16.3 Effect of Heavy Vehicle Exhaust to the Height of a Barrier

Due to the presence of heavy vehicles, the noise source location of a road raises a higher position along a vertical measurement coordinate to a height about 2.5 meters above road pavement. Therefore the receiver location is lowered. In order to attenuate the noise, the height of the barrier required has to be increased. Figure 3.9 shows this effect.

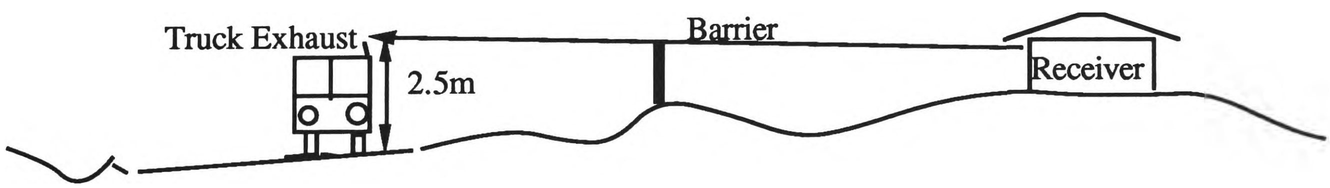


Figure 3.9 Effect of Heavy vehicle exhaust to barrier efficiency (After Bolt, 1976)

The height of a barrier increases on roadway sectors which have up-grade conditions. The higher noise reduction requirement arises due to higher noise levels emitted and the source position of the heavy vehicles climbing up hill or road elevation.By allocating 3 dimensional coordinates for the receiver and the source position a prediction of required barrier height should be done.

3.16.4 Barrier Correction of CORTN Model

CORTN (UK- DoE, 1975) has provided potential barrier corrections and those methods were applied in this thesis. As per CORTN method, effects of barrier attenuation and the soft ground attenuation are assumed to be non additive as the diffracted sound is not in close proximity to the ground. A typical barrier configuration is given in Figure 3.8 and the effective barrier mass required as per barrier height is given in Table 3.10.

The minimum barrier mass required to ensure that noise levels transmitted does not contribute significantly to the received sound level at the observer location is given in CORTN method as follows:

$$m = 3 \text{ X } 10 \; - \frac{(A + 10)}{14} \; kg/m^2 \qquad (3.13)$$

where

m = Minimum superficial mass of the barrier

A = Potential barrier correction (negative)

Mass per unit area of a barrier is the prime factor on which the effectiveness of a barrier depends on. Cracks and gaps in a barrier reduces its effectiveness, and hence, it is a must that the barrier materials are properly secured to form a strong non leaking structure. A barrier has to meet aesthetic, economic and long lasting criteria in addition to the acoustic performance. Effect of barrier height and mass on noise levels is given in Table 3.6.

Table 3.6 Effect of barrier height and mass on noise levels

	Effective Barrier Height			
	No Barrier	Barrier of zero height	1.5 meter	2.5 meter
Basic Noise Level	75.4	75.4	75.4	75.4
Barrier Correction	0	-5.0	-8.7	-11.5
Ground attenuation	-6.9	-3.3	-3.3	-3.3
Reflection	+2.5	+2.5	+2.5	+2.5
Final value of L_{10} (18 h)	71.0	69.6	65.9	63.1
Minimum Barrier Mass Required (kg/m^2)	-	1.3	2.4	3.9

Required minimum barrier height for Table 3.10 was calculated and the barrier correction given as per UK DoE method. Barrier correction of UK DoE is shown in Figure 3.10.

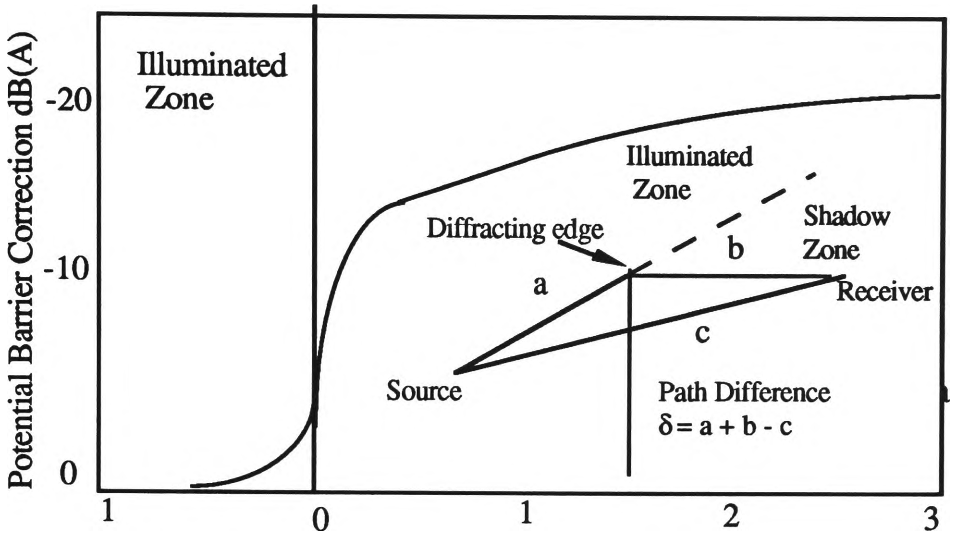


Figure 3.10 Barrier correction of CORTN (After U.K. DoE, 1975)

The attenuation provided by a barrier depends upon the ratio of effective height of it to the wave length of noise. The greater the barrier height to wave length ratio, the higher the attenuation. Direct transmission can be neglected and only the diffracted sound rays will affect the height of the barrier. This effect has been pointed out by Turner and Pretlove (1991). Shielding provided by walls and screens has been shown in Figure 3.11.

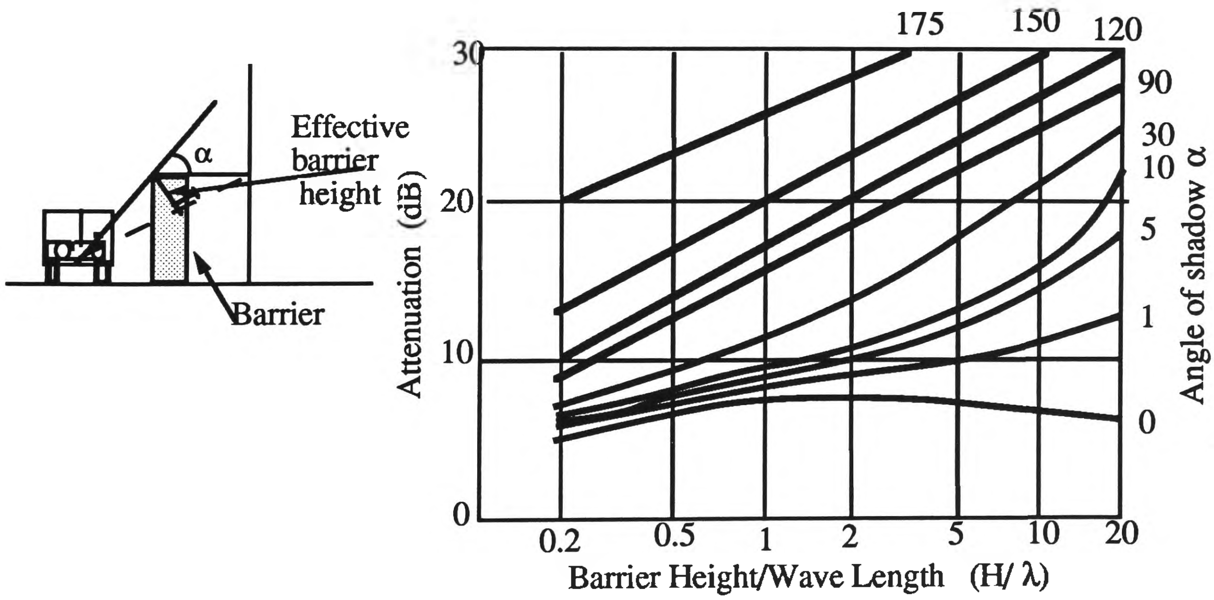


Figure 3.11 Shielding provided by solid barriers.(After Pretlove, 1991)

3.16.5 Transmission Loss Through Barriers

The reduction of acoustical energy transmitted through a barrier may in certain situations compromise the effectiveness of it. The resistance to transmission is called the "transmission loss" (TL). This is the ratio of incident noise energy to transmitted noise energy (Bolt, 1976). That ratio can be given as:

$$TL = 10 \log \frac{(\text{Incident noise})}{(\text{Transmitted noise})} \qquad (3.14)$$

Where

TL = Transmission loss

The larger the TL, the less noise energy is passed through the barrier. The transmission loss of any barrier wall depends upon the surface weight of the wall, stiffness, loss factor, angle of incidence, and the frequency of the approaching noise. According to the mass law, the transmission loss always increases by 6 dB(A) whenever the mass of the barrier is doubled. Figure 3.12 shows the incident, reflected and transmitted sound waves as relevant to a barrier.

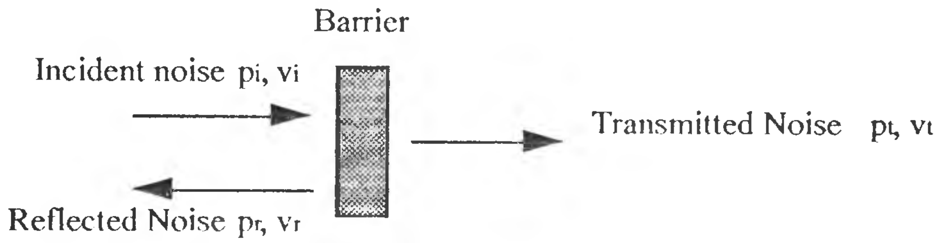


Figure 3.12 Incident, reflected and transmitted sound waves (After Turner and Pretlove, 1991).

Accordingly, the conditions prevailing in the wall are:

for velocity

$$v_i + v_r = v_t \qquad (3.15)$$

for force

$$p_i + p_r - p_t = (mi\omega)\, v_t \qquad (3.16)$$

where

ω = Circular frequency

v_i = Incident velocity (m/sec)

v_t = Transmitted velocity (m/sec)

v_r = Reflected velocity (m/sec)

p_i = Incident force (kN)

p_t = Transmitted force (kN)

p_r = Reflected force (kN)

m = Unit area mass of barrier material (kg)

As the pressure and velocity are directly proportional to each other the following relationship of pressure and velocity have been derived:

$$\left.\begin{aligned} p_i &= \rho c v_i \\ p_t &= \rho c v_t \\ p_r &= \rho c v_r \end{aligned}\right\} \quad (3.17)$$

By substituting the equation 3.17 in 3.16, and elimainating v_r by using equation 3.15, the following result can be obtained:

$$\frac{p_i}{p_t} = \left(1 + \frac{m_i\omega}{2\rho c}\right) \qquad (3.18)$$

Where

c = Speed of the waveform,

ρ = Density of the barrier material

Using logarithmic units to describe the TL in dB:

$$TL = 10 \log 10 \left|\frac{p_i}{p_t}\right|^2 = 10 \log_{10}\left[1 + \left(\frac{m\omega}{2\rho c}\right)^2\right] \qquad (3.19)$$

In all practical situations $\left(\frac{m\omega}{2\rho c}\right) >> 1$

Hence, the equation 3.19 can be expressed as:

$$TL = 20 \log_{10} \left(\frac{m\omega}{2\rho c}\right)$$

Using the unknown properties of air, this can be restated as:

$$TL = 20 \log_{10} m + 20 \log_{10} f - 42 \qquad (3.20)$$

Here, the value 42 has been selected taking into account all angles of incidence on the barrier that is 42 dB(A) (Turner and Pretlove, 1991).

The surface weight density is the most important parameter which affects the transmission loss of a barrier. The heavier the barrier the less noise will pass through it. If a barrier is designed to attenuate 5 to 10 dB(A), a larger portion of the noise will pass through the barrier without any attenuation. If the design feature of a barrier is about 20 dB(A) over the top, it is expected to reduce the transmitted noise energy to a comparable amount, and the transmitted energy should be 3 to 6 dB(A) less than noise over the top of the barrier. Therefore, the transmitted noise decreases the barrier attenuation by about 1 dB(A) (Baranek and Newman, 1976).

3.16.6 Barrier Failure due to Holes in Them

Holes in the barriers may severely reduce the transmission loss of barriers. For example, assume an 84 dB(A) exists at the source side of a barrier and the TL of the barrier is 20 dB. If the barrier is without holes the noise at the receiver side of the barrier would be 60 dB(A) provided no noise is diffracted over the top.

If the open area in the barrier is assumed as 10% the effect of this open area over the transmission loss can be calculated as follows.

- Ninety percent of the noise energy hits the barrier itself and is reduced by 20 dB(A) due to the transmission loss of the barrier. From Table 3.7 (Anderson, et al., 1973) 90% of 84 dB(A) is 84 - 0.5 = 83.5 dB(A). In decibels almost all the noise energy hits the barrier itself. This 83.5 is reduced by 20, yielding 63.5 dB(A).
- Ten percent of the noise energy hits the open area (hole), and is increased by 6 dB(A). From the table 3.8, 10% of the 84 dB(A) is 74 dB(A). This is increased by 6 dB(A), yielding 80 dB(A). Finally, the total energy is the logarithmic sum of 63.5 dB(A) and 80 dB(A) is 80.1 dB(A). Hence the barrier has provided only a 3.9 dB(A) attenuation.

Barrier attenuation drastically lies in the logarithmic nature of the noise. Eventhough a barrier itself eliminates 90% of the noise energy, this is only a reduction of 10 dB. Even in extremely successful barriers in which the barrier eliminates about 99% of the energy, still the attenuation is only 20 dB.

The second reason for the barrier inefficiency when there is a hole available in the barrier is due to 6 dB(A) increase in noise through the hole; that is, the amplification due to the hole is TL_{hole} = -6 dB. This increase is due to pressure doubling at the barrier surface. In other words, more energy is passed through the hole than is straight incident to it.

As seen in Table 3.8 the maximum transmission loss through a barrier hole is reduced even by a very small hole in the barrier, and the absorptive surfaces of the barrier can improve this transmission loss. It is interested to note that a very good absorptive treatment can eliminate this 6 dB amplification through the hole. For the calculation of the effectiveness failure of a barrier caused due to a hole in it was given by conversion Table 3.7.

Table 3.7 Conversion of percentage of open area of a barrier to decibels (After Anderson, et al., 1973)

Percentage of Total Area	To be Subtracted from Incident Level
100	0
90	0.5
80	1
63	2
50	3
40	4
25	6
16	8
10	10
6	12
4	14
2.5	16
1.6	18
1	20
0.6	22
0.4	24
0.25	26
0.16	28
0.1	30

Table 3.8 Maximum transmission loss of barriers with holes and with or without absorption (After Anderson et al., 1973)

	Maximum Transmission Loss Possible on Source Side of a Barrier (dB)	
Open Area of the Barrier (%)	Without Absorption	With absorption
50	0	3
10	4	10
5	7	13
1	14	20
0.5	17	23
0.1	24	30

3.17 FIELD INVESTIGATIONS OF NOISE BARRIER PERFORMANCE

In order to determine the effectiveness of traffic noise barriers in reducing traffic noise, a number of surveys has been conducted by the author during the period between 15th May and 20th December 1991, in Wollongong area to collect required data. The data were analysed in order to determine the acoustic performance of noise barriers erected alongside the arterial roads of Wollongong area of the Illawarra region of New South Wales. The findings of extensive measurements conducted at twenty one sites show that noise attenuation levels of different types of noise barriers are readily correlated with both the barrier material, the thickness and the height of the barrier.

3.17.1 Instrumentation and Analysis for Noise Barrier Types Surveys

The output of a Bruel and Kjaer type 2215 noise level meter with 'A' weighting was recorded on Bruel and Kjaer type 2306 continuous chart noise level recorder which has 1/3 octave band analysis and alphanumeric printing facilities. The paper speed of the printer was set to 3 mm per second, and the writing speed was set to 100 mm per second at AC log mode. Noise Level meter and the level recorder have been checked for the charge level of the battery. The noise level meter was mounted on a tripod and was connected to the continuous chart level recorder. The level meter was calibrated with Bruel and Kjaer type 4230 piston phone to 94 dB. Kustom KR 11 radar speed level meter has been used to measure the speed of the traffic flow.Wind speed had been measured with AM 5000 Ameometer type air velocity meter, and the relative humidity had been measured with Branan Hygrometer. Temperature was obtained using a Celcius Laboratory Thermometer.

For the effectiveness of barrier types surveys statistical noise percentage levels L_{10} levels and L_{eq} levels have been computed using the print outs of the level recorder, and for the effectiveness of barrier heights surveys, the recorded noise levels were analysed using a third octave noise level analyser (B&K 1613). Figure 3.13 shows the map of the survey area and the survey sites.

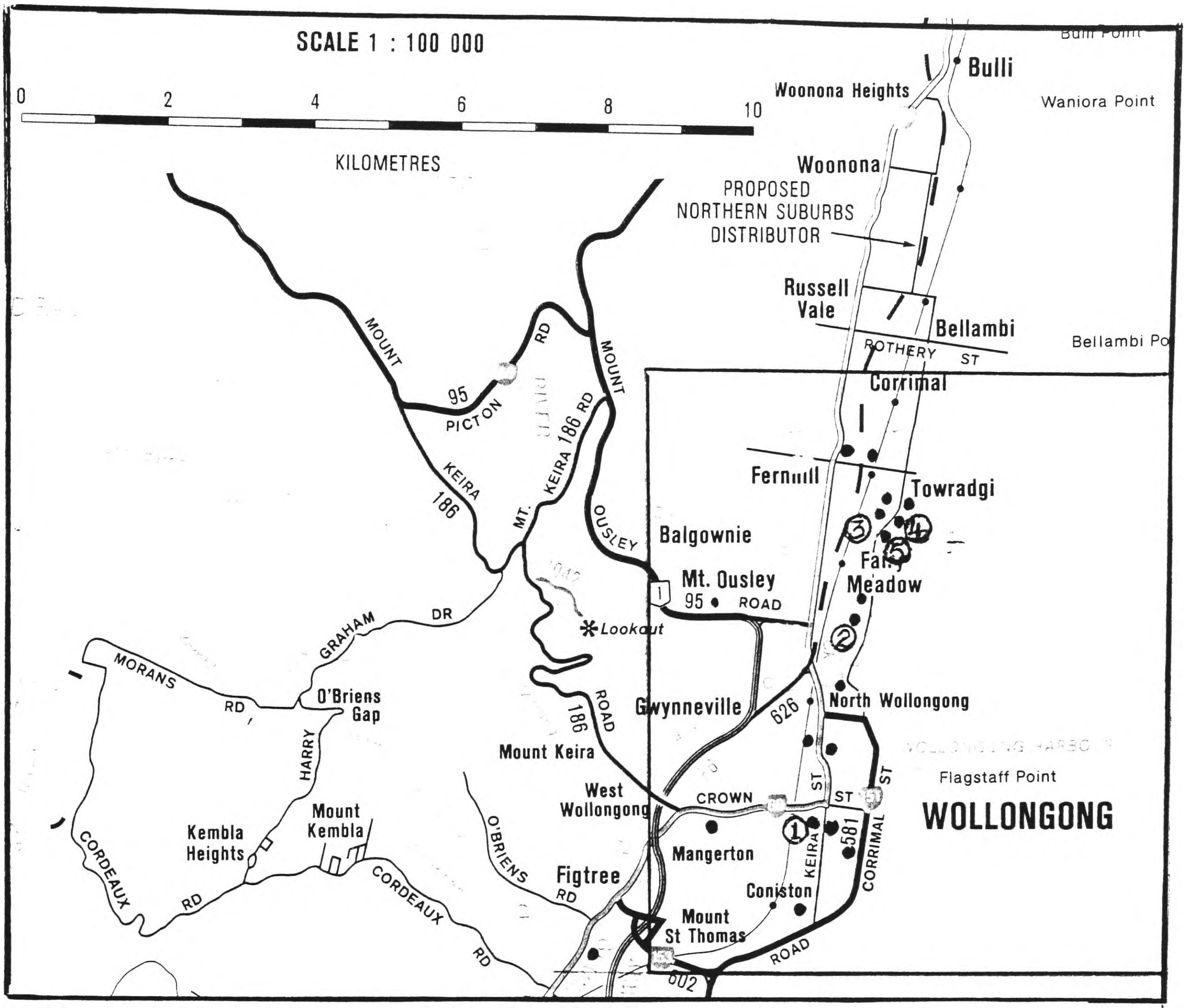


Figure 3.13 The map of research survey sites

The total number of sites investigated was 21 and five among these were selected to clarify the actual attenuation and the effectiveness of five types of barriers found in the Wollongong area. The main aim of the experiment was to measure the efficiency of screening effect of the existing types of noise barriers in residential areas.

The sites selected were along four lane and six lane roads where plane roadway grade and a free flow traffic conditions available. The width of each traffic lane is 3.5 metres. Figures 3.18 to 3.22 shows the types of actual barriers investigated and their sites.

3.17.2 Measurements in Keira Street, Fairy Meadow and Towradgi

The main sites where the measurements were done in the towns of Fairy Meadow and Towradgi in Wollongong area. The typical traffic noise barriers were found erected in these areas have been selected as the suitable sites by the author. The objective of the research survey was to determine the effectiveness of those barriers by using the actual measured and the predicted noise levels (by using CORTN method) .

The following measurement technique was applied. Sound level meter was used to take peak hour traffic noise measurements during peak hours; once in front of the barrier (10 meters from the centre of the road) and the next behind the barrier (E.g 2.5 meters from the barrier or 7.5 meters away from the centre of the near side traffic lane of a two lane two way road). Recordings were noted using a voice commentary at peak points to show different classes of vehicles. The noise level measured by noise level meter B&K 2215 has been transferred to the connected level recorder B&K 2215 with alphanumeric printing facility. has been used in the analysis. Manual traffic counts have been done and percentage of heavy vehicles also were recorded for one hour periods, and peak noise levels (L_{10}) were measured for 15 minute periods. Average speed levels were taken according to Kustom KR 11 radar speed level meter. All the measurements were done over the grass land. Table 3.9 shows the data related to the location of each type of noise barrier investigated.

Table 3.9 Data related to different barrier locations

Site Number	Type	Location	Roadway Gradient	Distance from Road edge(m)	Facade Reflection
1 (F), 1 (R)	E	Keira Street, Wollongong	up hill	7.5	yes
2 (F), 2 (R)	B	Soccer Grounds F/Meadow	up hill	7.5	nil
3 (F), 3 (R)	A	Carters Lane, Towradgi	plane level	7.5	yes
4 (F), 4 (R)	D	Carters Lane, Towradgi	plane level	7.5	nil
5 (F), 5 (R)	C	Carters Lane, Towradgi	plane level	7.5	nil

Legend (F) = In front of barrier, (R) = Behind the barrier

Table 3.10 show the climatic conditions prevailed during the survey periods.

Table 3.10 Climatic conditions during surveys

Site Number	Type	Time	Weather	Temperature Centigrade	Humidity	Wind Speed -km/h and Direction
1 (F)	E	8.50-9.05	fine-sunny	23	62	5.2-East
1 (R)	E	9.10-9.25	fine-sunny	23	62	5.2-East
2 (F)	B	9.30-9.45	cloudy	24	80	8.0-East
2 (R)	B	10.30-10.45	cloudy	24	80	8.0-East
3 (F)	A	11.00-11.15	fine-sunny	24	60	6.2-East
3 (R)	A	11.30-11.45	fine-sunny	24	60	6.2-East
4 (F)	D	14.30-14.45	fine-sunny	26	60	6.6-East
4 (R)	D	15.00-15.15	fine-sunny	26	60	6.6-East
5 (F)	C	16.00-16.15	fine-sunny	26	60	5.5-East
5 (R)	C	16.15-16.30	fine-sunny	26	60	5.5-East

Legend (F) = In front of barrier, (R) = Behind the barrier

Table 3.11 shows the measured L_{10} values of and the traffic conditions prevailed during the survey.

Table 3.11 Measured L_{10} noise levels and relevant traffic conditions

Site Number	Traffic Flow veh/h	Mean Speed km/h	% of HGV	Noise (front) Barrier dB(A)	Noise behind Barrier dB(A)
1	1137	60	10.0	66.0	59.2
2	1033	71	14.1	73.2	64.5
3	1470	66	12.2	70.1	62.3
4	1459	72	16.0	75.0	69.4
5	1312	59	15.0	72.4	66.7

The UK, DoE procedure was applied with the correction factors such as traffic flow, speed, percentage of heavy vehicles, roadway gradient, soft ground propagation , potential barrier correction, angle of view. In order to predict the noise level at reception point (noise levels after the actual attenuation), the noise at 10 meters away from the nearside road edge has been predicted using the above method. Using the data for the traffic flow, determined the noise level at 10 m from the roadway corresponding to no heavy vehicles, percentage of the gradient (zero here) and the conventional road surfaces as per correction in Figure 3.14.

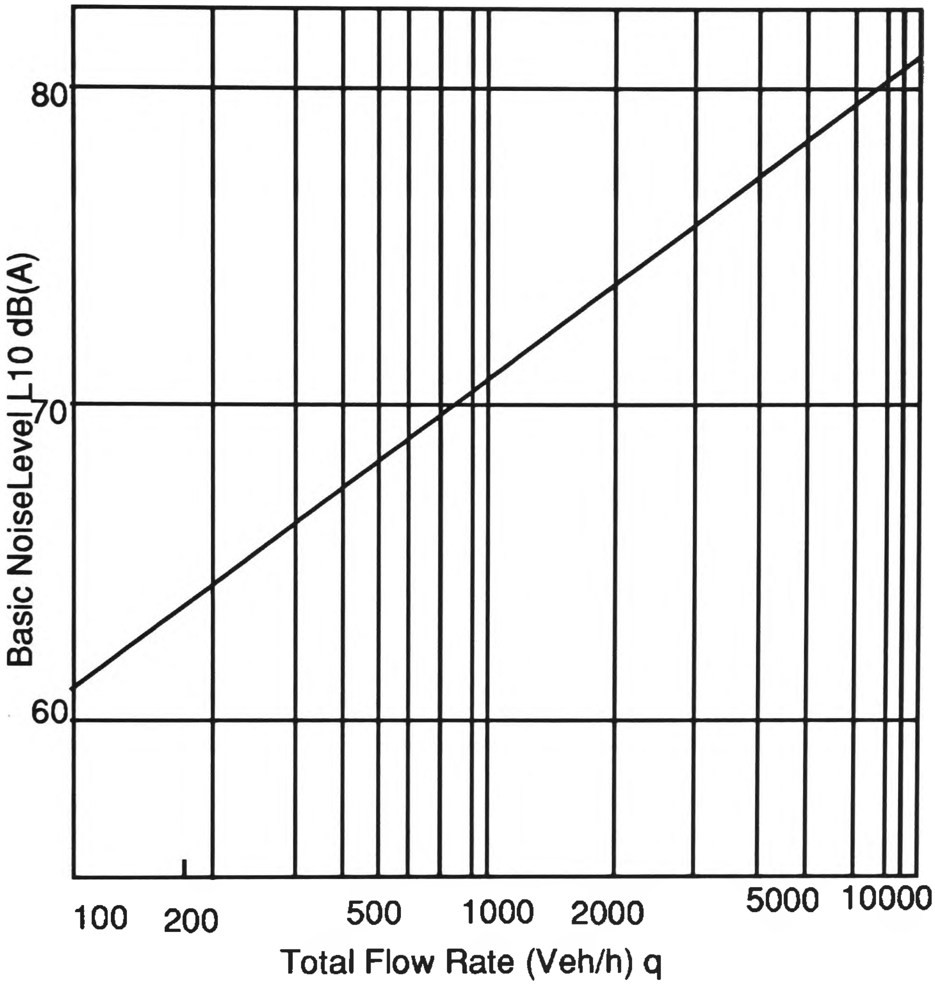


Figure 3.14 Correction base on hourly flow rate (v = 85 km/h, p = 0, g = 0)
(Modified from UK DoE, 1975)

Then by applying the correction factor taking the speed and the percentage of heavy vehicles into account as per Figure 3.15. The correction factor for the actual mean speed is applied as 0.3 g where g is the percentage of the gradient. Figure 3.15 shows the correction for the mean traffic speed and percentage of heavy vehicles as applied in CORTN (UK DoE, 1975).

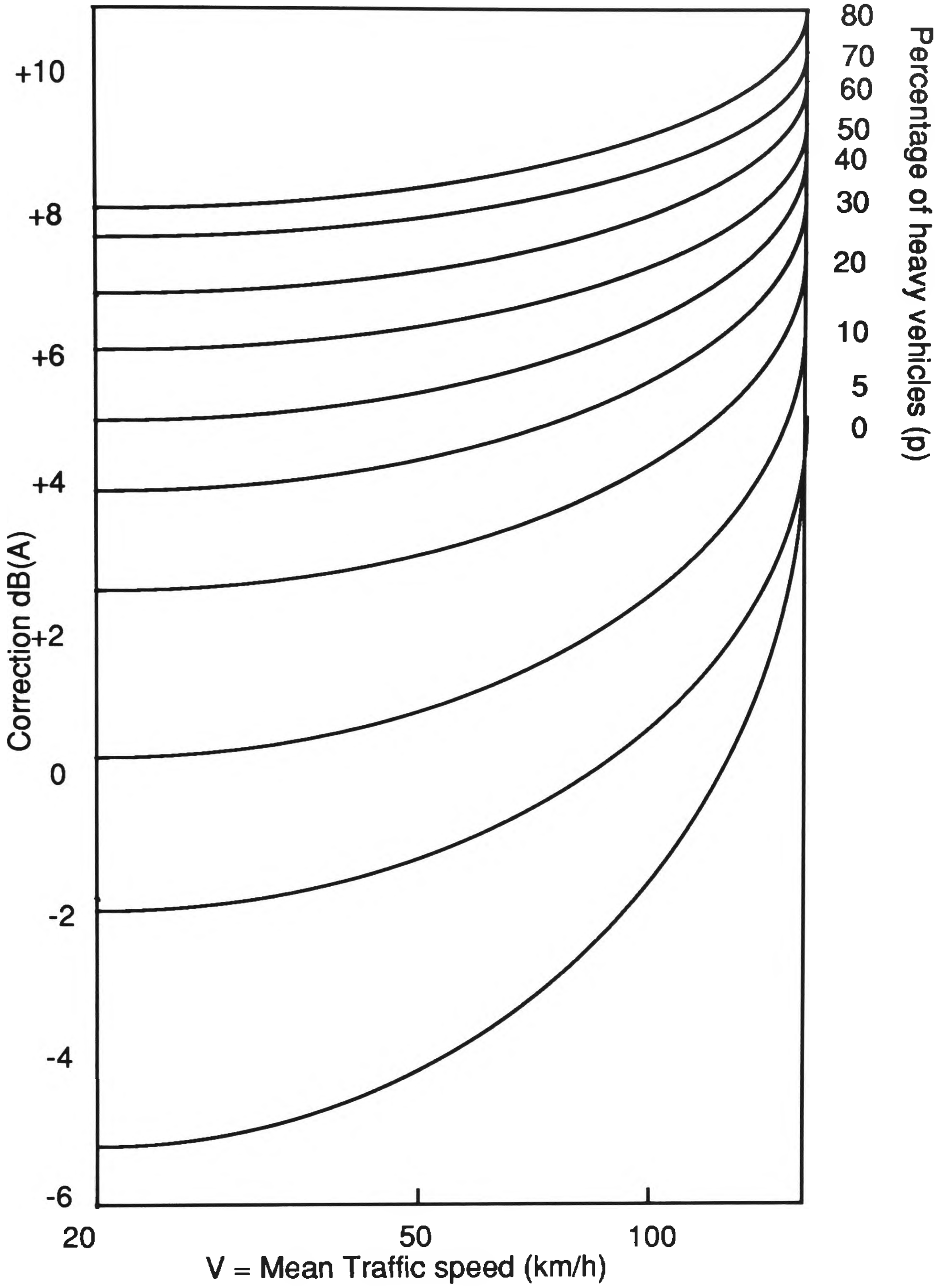


Figure 3.15 Correction for speed and percentage of heavy vehicles
(After UK DoE, 1975)

Throughout the prediction process, the line of the source of the traffic noise was taken as 10 m from the centre line of the road and 1.2 m high.

Correction factors for the propagation over the soft ground was applied then as per Figure 3.16.

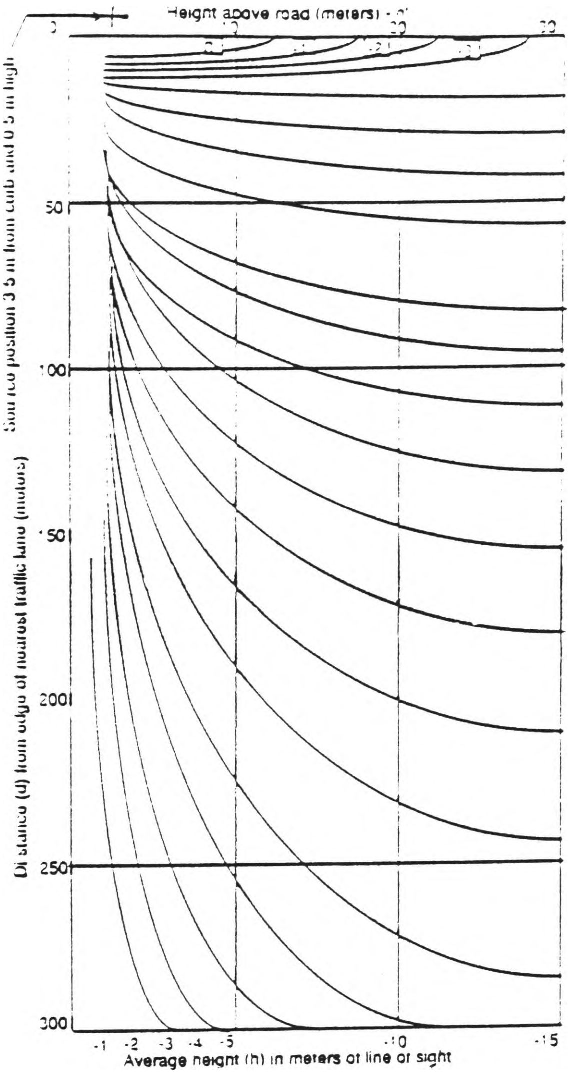


Figure 3.16 Correction for ground effect over the soft ground (After UK DoE, 1975)

The correction for screening was applied at the reception point of a barrier, calculated using the propagation correction of Figure 3.10. This correction was performed according to the correction read from the curve at the appropriate value of the path difference (a+b-c) as per the inset figure of Figure 3.10. The "illuminated zone" of this Figure was used to evaluate the correction for small screening effect for the receiver points which can just see the source over the top of the barrier.

In such cases like very low barriers, the correction for screening may be less than the difference between hard ground and and soft ground distance corrections. In cases where the propagation is over soft ground the noise levels at the reception point has been evaluated for grassland ignoring the barrier

According to the field surveys done, there are two main categories of traffic noise barriers available in Wollongong area of Illawarra region of New south Wales:

o Reflective barrier

o Absorptive barrier.

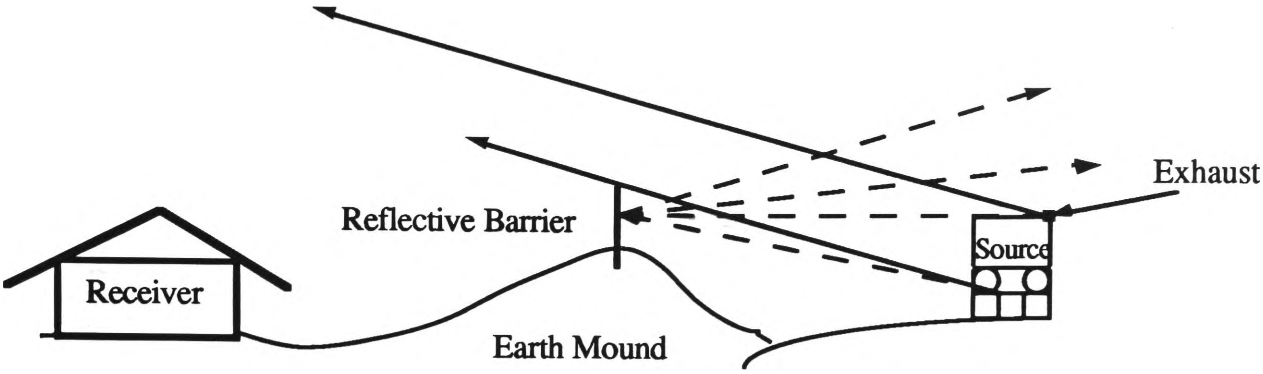
Each of the above categories have different characteristics which depend on the location and relationship to the source of noise, availability of other reflective surfaces, and the influence of the adjacent properties within the line of sight.

(1) Reflective noise barriers

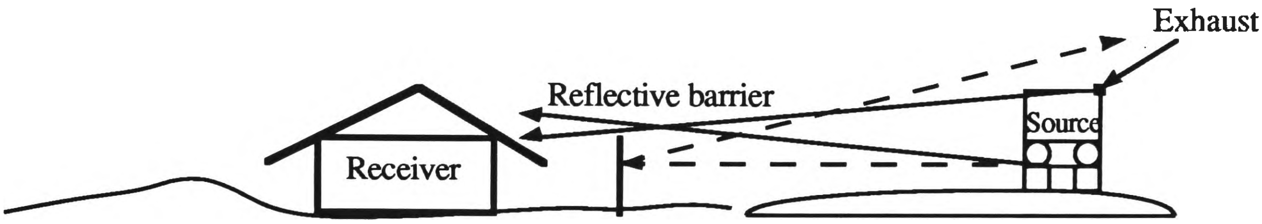
These barriers reflect the noise energy thus directly reducing the impact of traffic noise to the residents of the houses behind them. Some of the schools and play grounds are protected by these barriers too. However the occupants of the houses directly opposite to these type of barriers are affected by them due to reflected beam of noise.

(2) Absorptive noise barriers

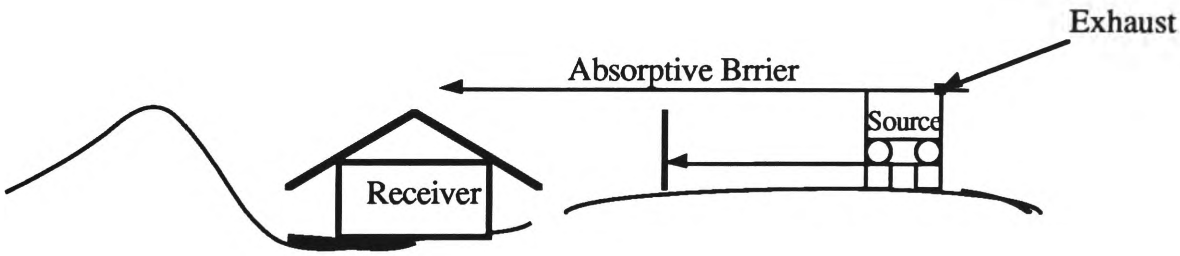
These absorptive type barriers are designed and made to absorb the traffic noise by forcing the molecules of air to move in and around the porous area of them and their tiny fibre material and convert the noise energy to mechanical or heat energy. Only a little percentage of the noise energy entered the barrier is reflected outwards. Figure 3.17 shows the effects of the reflective barriers and absorptive barriers.



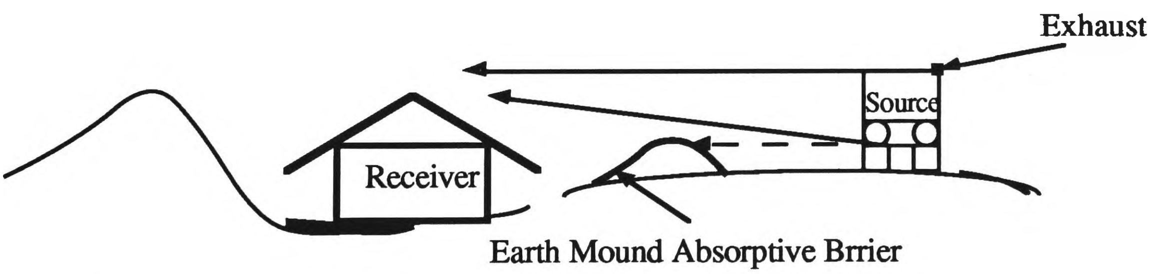
Reflective barrier Mounted on an earth mound



Reflective barrier erected on ground



Absorptive barrier erected on the ground (clay brick type)



Earth Mound type as an absoptive barrier

Figure 3.17 Effects of Reflective and absorptive barriers

3.17.3 Details of Traffic Noise Barriers Investigated

In this research, five types of traffic noise barriers which belong to either absorptive or reflective barrier categories have been subjected to investigation and their description is given below

Type 'A' Barrier (Wooden paling type)

Either horizontal or vertical plank (paling) type barriers are constructed with 50 mm thick wooden planks (either Pressure Treated Pine (P.T.P) or any other hard wood) bolted together to overlap each other, bolted to either square or round timber or concrete posts. These are usually 1.8 meters to 2.1 meters high. Some of them are constructed on earth mounds for higher effectiveness. The thickness are usually about 50 mm. These planks are bolted to hardwood rails for strength. The noise attenuation is obtained due to the thickness of the timber planks overlapping each other. This type of barriers have usually been built in place of security fencing and are usually painted with wood preservative or a hand paint (lacquer) to make them aesthetically attractive. Their maintenance is easy. The barrier under consideration was 2.1 metre high.

Figure 3.17 (a) Type 'A' Barrier

Figure 3.18 (b) Type 'A' Barrier

Type 'B' Barrier (Earth mound type)

Earth mounds also have been used as noise barriers in Wollongong region. Usually these mounds have been made during construction stages. They have about 4:1 slopes. They are aesthetically attractive. Economy of constructing the earth mounds as noise barriers depends on the cost of the right - of - way. It has been noticed that the earth mound type noise barriers can be economically constructed where excess cut soil is freely available. Grass growing over the earth mounds increase the visual effect of the earth mound type noise barriers, in addition the grass may give a certain attenuation due to ground cover. These type of barriers require no maintenance other than planting the grass to avoid the erosion due to rain. This type of barrier is the most widely used type for noise attenuation of playgrounds. A survey site for type 'B' barrier is given in Figure 3.19. The barrier under consideration was 3 metres high.

Figure 3.19 Type 'B' Barrier

Type 'C' Barrier (Corrugated or plane asbestos type)

These barriers are constructed with corrugated asbestos cement sheets fitted on to a wooden or steel frame fence. These sheets are usually 9 mm thick and the width of the sheets about 400 mm. Usually the bottom edge is buried in the ground hence it does not require a plinth to prevent noise leak through the bottom edge and the ground. Their height is usually limited to about 2 meters (usual length of an asbestos cement sheet). Figure 3.20 shows a survey site where the effectiveness of type 'C' barrier was measured. The barrier under consideration was 1.5 metres high.

Figure 3.20 Type 'C' Barrier

Type 'D' Barrier (Corrugated Aluminium steel sheets type)

Steel type noise barriers are usually made with corrugated steel sheets (E.g Lysaght manufactured Trimdek Hi-Ten Zincalume Steel sheets). Most of them are made with Zincalume metal alloy and are coated with fluropolymer enamel paint to give them anticorrosive and aesthetic properties.

They are usually about 0.4 to 0.7 mm thick 200 mm long and 400 to 750 mm wide. They have a choice of colours to suit with the requirements of the landscaping for visual improvement. Figure 3.21 shows a type 'D' barrier site. The barrier under consideration was 2 metres high.

Figure 3.21 (a) Type 'D' barrier

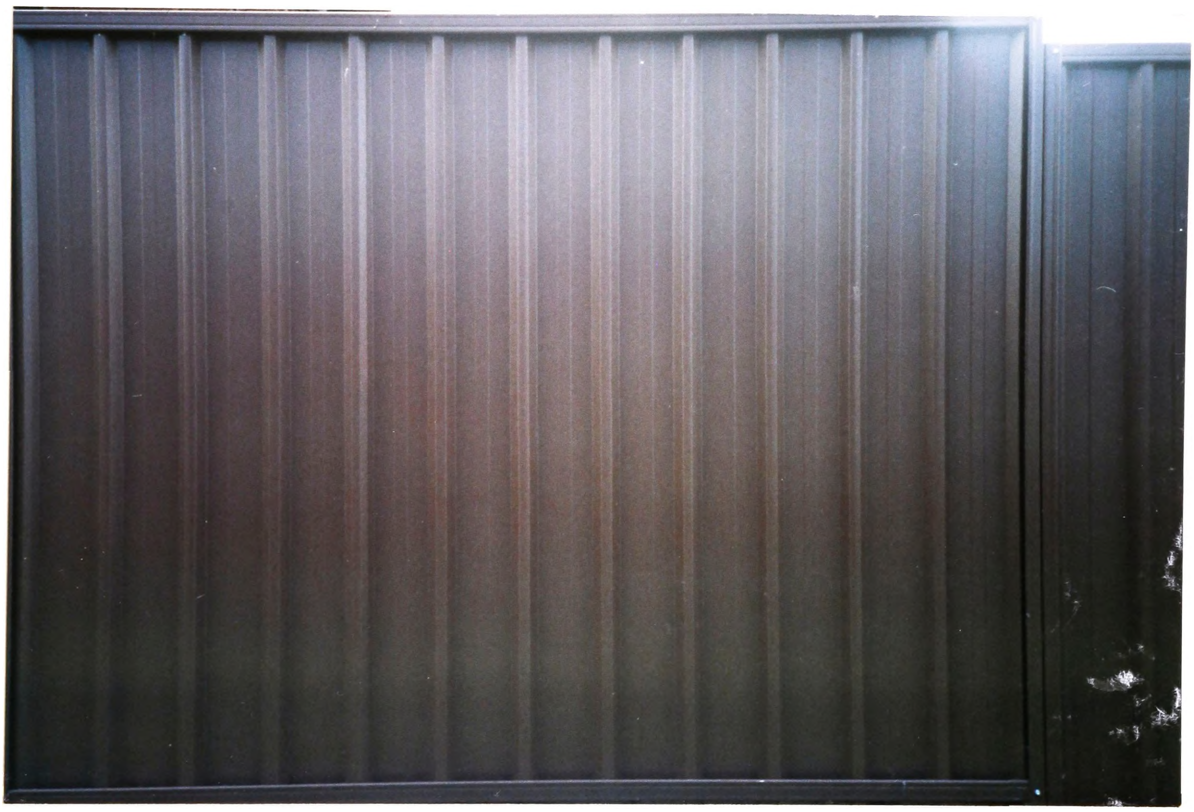


Figure 3.21 (b) Type 'D' Barrier

Figure 3.22 shows a survey site for barrier type 'E'.

Figure 3.22 (a) Barrier type 'E'

Figure 3.22 (b) Barrier Site 'E'

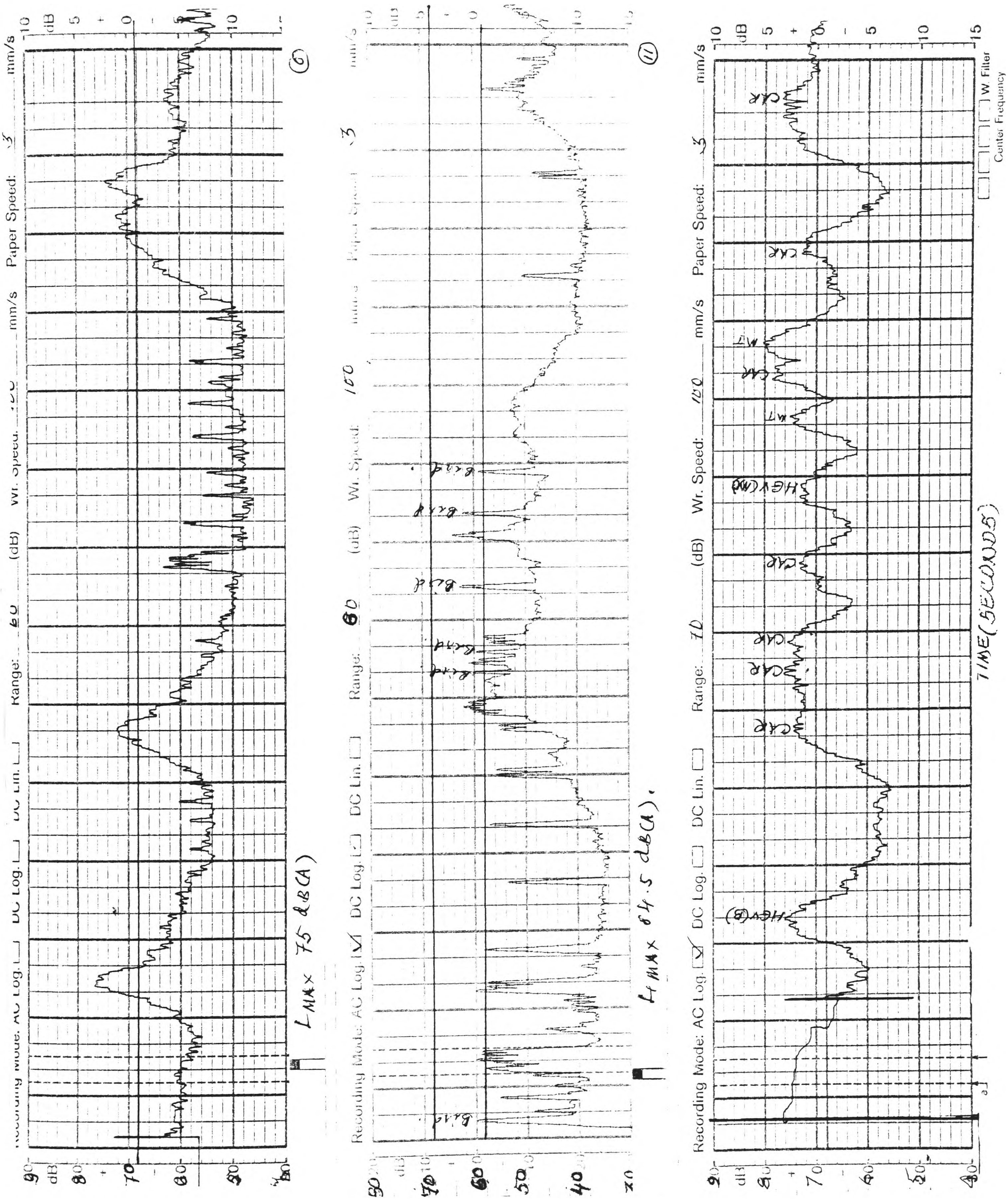
Type 'E' Barrier (Clay brick type):

The other type of noise barriers which have been found more effective are made of clay bricks (Type "E"). Eventhough their construction cost is fairly higher comparative to the 4 types of barriers described above, as far as noise attenuation is concerned, they have been found very effective. Due to the thickness, robustness, and the mass, they provide a higher noise attenuation. There is no noise leakages through the wall unless there is a larger open area. They do not have any leakage between barrier and the ground due to the fact that they have been constructed on a foundation lain on the ground with cement mortar. Inter brick bondage also is done with the cement mortar. Visual improvement provided by brick type noise barriers is very high. In addition they do act like strong security walls when they are constructed to a height above line of sight of about 2 meters. The clay brick barrier under consideration was also 1.2 metres high. Figure 3.23 shows a house facing away from the road which gives a barrier effect.

Figure 3.23 Houses with doors and windows facing away from the road.

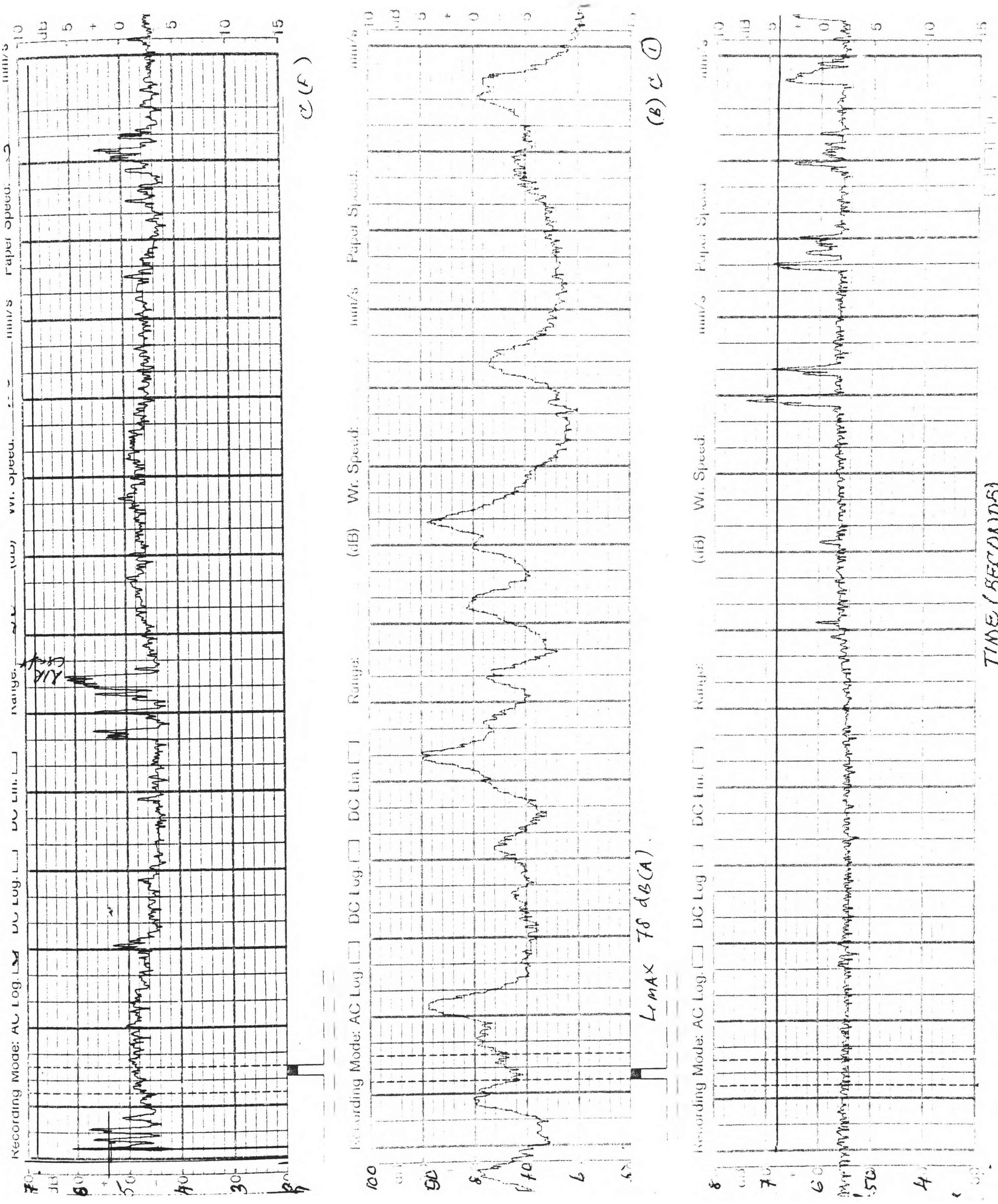
3.18 ANALYSIS OF THE RESULTS

Figures 3.24 (a), (b), (c) show the level recorder print-outs obtained for five different types of noise barriers tested by the author of this thesis.



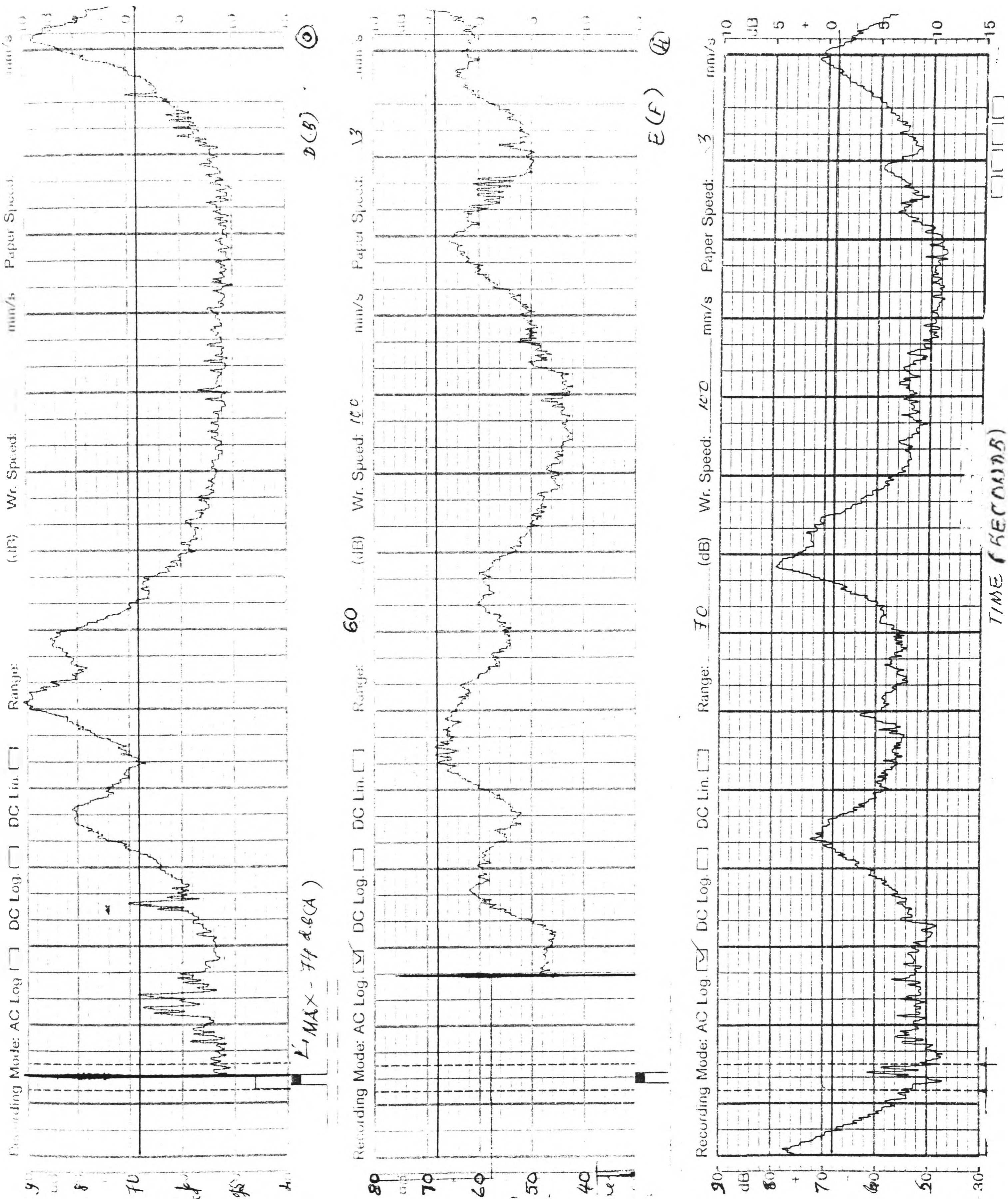
Type A (Front) Type A (Behind) Type B (Front)

Figure 3.24 (a) Level recorder print-outs for different Barrier types



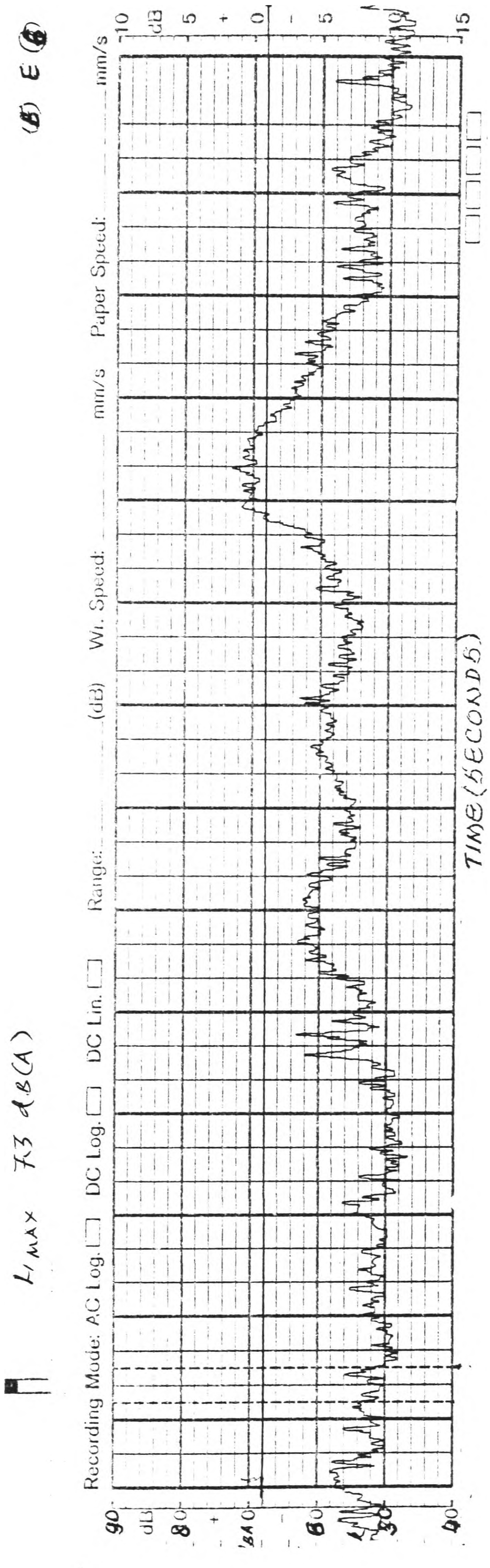
Type B (behind) Type C (Front) Type C (Behind)

Figure 3.24 (b) Level recorder print-outs for different Barrier types



Type D (Front) Type D (Behind) Type E (Front)

Figure 3.24 (c) Level recorder print-outs for different barrier types



Type E (Behind)

Figure 3.24 (d) Level recorder print-outs for different barrier types

The summary of the test results is set out below in Tables 3.12, 3.13, 3.14, and 3.15. It shows clearly the attenuation achieved by each type of barrier in terms of approximate number of peak levels shown in the level recorder trace investigated and the prevailing noise levels at no barrier situation.

Table 3.12 Calculated transmission loss (Reference pp 210 of Appendix 4)

Barrier Type	Calculated Transmission Loss [dB(A)]
A	14.09
B	91.58
C	23.11
D	33.56
E	70.5

Table 3.13 Summary of results (Reference pp 150 of Appendix A).

Site-with barrier (+), no barrier (-)	Type	Time 24 H Clock	Background Noise dB(A)	Maximum Peak- dB(A)	Approx.No of Peaks/ Hour above 68 dB(A)
1 (+)	E	8.50-9.30	54	73	8
1 (-)	E	9.10-9.25	49	80	44
2 (+)	B	9.30-9.45	56	58	0
2 (-)	B	10.30-10.45	42	84.5	211
3 (+)	A	11.00-11.15	55	75	31
3 (-)	A	11.30-11.45	50	84	78
4 (+)	D	14.30-14.45	51	74	13
4 (-)	D	15.00-15.15	40	91	86
5 (+)	C	16.00-16.15	54	78	20
5 (-)	C	16.15-16.30	50	87.5	75

Table 3.14 Summary of comments

Site-with barrier (+),no barrier (-)	Type	Comments
3 (+)	A	Attenuation achieved was 9 dB(A). Noise levels heard above the back ground level was 20 dB(A). No. of peaks heard was 31 where at no barrier situation it was 78. Poor propagation loss was due to the large % of open area (10%) in the barrier surface, low thickness, and low mass per unit area. It has been noted that the timber planks had gaps between them.Timber paling type barriers be constructed by properly overlapping joints of the timber palnks , and closing the gap between barrier and ground sealing with cement, to achieve the maximum transmission loss possible.
3 (-)	A	Noise level was 34 dB(A) above the back ground level, and the number of peaks exceeding the acceptable level was 78 dB(A). No attenuation due to no barrier situation.
2 (+)	B	Attenuation achieved was 26.5 dB(A) and calculted transmission loss was 91.58 dB(A) which were the highest figures among barriers investigated.No.of noise peaks above acceptable level [68 dB(A)] observed was nil. Difference between trafficand back ground noise level was only 2 dB(A) which is negligible.The transmission loss has not been affected by any open area, giving maximum attenuation. Calculated attenuation according to height of barrier is 35.8 dB(A), and actual attenuation achieved was only 26.5 dB(A). It proved to be the most effective traffic noise barrier which can be erected very economically and effectively where filling material and the right-of-way is freely available. A high level of transmission loss is possible due to higher thickness and the mass of the barrier material of earth mound type barriers.

2 (-)	B	Traffic noise level exceeded more than 100% above the back ground noise level, and the number of noise peaks heard exceeding the acceptable level was very high; (211). Flow, speed and the percentage of heavy vehicles prevailed were same as att other sites. Attenuation is nil.
5 (+)	C	Attenuation achieved was 9.5 dB(A).Calculated transmission loss was only 23.11 dB(A), which is lower than all the other barrier types investigated. Calculated attenuation possible due to the height was 28.5 dB(A). Reason for poor transmission loss was due the large open area (10%) (Reference table 3.9), low mass per unit area and the low thickness. It is required to increase height and minimise open area , if a higher efficiency is required from this type of barriers.
5 (-)	C	Back ground noise level has been exceeded by 30.5 dB (A). Number of peaks heard exceeding the acceptable level was 55 above 20 observed with barrier situation.
4 (+)	D	Attenuation achieved was 17 dB(A). Eventhough the noise heard above the background was 23 dB(A), only 13 noise peaks exceeding the acceptable level had observed. Transmission loss factor [33.56 dB(A)] is far better than A and C types of barriers. The calculated attenuation due to the height was 32.2 dB(A) which is very closer to transmission loss. As far as visual effect and the efficiency are concerned this type of barrier is the most suitable device for residential noise abatement. The material and cost construction as per figures available was $ 3000 per 100 square meters. It is necessary to construct Zincalume steel type barriers with a height of 2.0 m, minimising open area, if a proper attenuation is required.
4 (-)	D	Noise level heard above the back ground level was 51 dB(A), and number of peaks observed above acceptable level was 86. Due to no barrier situation, the attenuation was nil. High peaks of noise was due to heavy traffic available.

1 (+)	E	About 5 to 7 dB(A) attenuation has been achieved by Clay Brick type barrier. No of peaks exceeded above 68 dB(A) was only 8. Calculated transmission loss for this barrier seen in Table 3.12 is [70.5 dB(A)], which is imferior only to the earth mound type. Calculated attenuation possible according to height of barrier as per appendix 4, is only 29 dB(A). But, large percentage of open area available in this barrier (10%), had reduced the efficiency of barrier (Reference table 3.7 and 3.8). If the expected attenuation from a clay brick type of barrier is above 29 dB(A), it will be constructed with a minimum height above 1.5 m, without leaving any open area suuroundin property.
1 (-)	E	Traffic flow, speed, heavy vehicle percentage and the related noise level outside barrier was same as observed in other four sites. Traffic noise level was 19 dB(A) more than the back ground noise level and the number of noise peaks exceeded were 44. Attenuation at this no barrier position is zero.

The final results of the tests conducted to identify the most suitable barrier type are presented in table 3.15.

3.19 CONCLUSION

According to the results it can be concluded that the earth mound type barriers are the best performers in traffic noise attenuation.The earth mound type barriers can be constructed more economically where cut and fill earth material and the right-of-way are freely available. They will give a better attenuation than the other types of traffic noise barriers and they are more suitable for the sites such as schools and the playgrounds. The Aluminium steel type barriers are the best barriers for residential noise mitigation. Corrugated asbestos and timber plain type barriers will give better results if they would have been properly constructed minimising that open area exposed. The clay brick type barrier would have been performed more effectively due to its heavy weight and the absorptiveness if the open area exposed had been minimised.

CHAPTER 4

EFFECTS OF TRAFFIC NOIS E REDUCTION DEVICES AT SOURCE

CHAPTER - 4

THE EFFECT OF TRAFFIC NOISE REDUCTION DEVICES AT SOURCE

4.1 INTRODUCTION

This chapter contains brief description of the various components of vehicles which contribute to the generation of noise, and an evaluation of previous research work in this field are also mentioned briefly. The chapter also reports on the field work carried out by the author for this study consisting of traffic drive-by noise surveys, experiments in tyre-road surface interface, engine RPM, and load relationship surveys, and an evaluation of the findings and the suggestions for the future research.

4.2 VEHICLE NOISE REDUCTION DEVICES

The noise abatement potential for trucks, cars and motor cycles can be determined through the assessment of feasible procedures for the noise producing components such as the engine, exhaust, cooling fan, intake, tyres and transmission and differential gearing, suspension and the body. Table 4.1 shows the noise levels of various components of a truck.

Table 4.1 Noise levels of different noise generating units of a truck (USEPA, 1972)

Noise Level dB(A) - 15 m away from a vehicle running at a speed of 60 km/h	Noise Source of the Vehicle
71	Engine
82	Exhaust
80	Intake
71	Cooling Fan
79	Tyres
84	Overall

4.3 ENGINE NOISE REDUCTION OF DIESEL TRUCKS

Noise produced by diesel trucks involves either modification of the engine or use of enclosures such as engine covers or partial enclosures. The following changes have been made by the General Motors - USA (Kennett, 1990) to the Detroit Diesel engine to effect the noise reduction:

(i) The piston and liner clearance reduction,

(ii) Reduced piston pin and upper connecting rod joint clearances and lubrication at high pressures.

(iii) Spur gear type oil pump had been replaced by a screw type oil pump.

(iv) Pump idler gear, changed from steel to nylon.

(v) Rear gear train changed to a belt.

(vi) Hydraulic valve lifters installed.

(vii) Pre combustion chamber type indirect injection is employed to reduce combustion noise.

(8) Separation of main bearing webs from the lower section of the cylinder block.

The above modification resulted in a net reduction in engine noise of 4 dB(A). Further research into this effect is in progress. These modifications are an improvement over the results obtained by the Cummins engine company which has achieved a maximum reduction of 3 dB(A) through engine modifications (Kenett, 1990).

According to the research so far carried out, the most promising methods for engine noise reduction are close fitting covers (shields), and engine enclosures. It is found out that laminated steel covers can be closely fitted over valve covers, oil pan, blower covers and cylinder block side panels to give a 3-5 dB reduction in noise. These and the other methods are discussed in detail below.

Total engine enclosures have been variously shown to provide from 8 to 15 dB(A), and from 12 to 23 dB(A) reductions. To be effective the engine enclosures need to be completely sealed, and covered internally with acoustic insulation. The enclosures can be made of steel, aluminium, and fibreglass. Partial enclosures or acoustic ducts achieve noise reduction values between those achieved by close fitting covers and total enclosures (Kenett, 1990).

Close fitting engine covers have added advantage of minimising vehicle maintenance. Because they are presently available for only cooled portions of the engine (not the exhaust manifold), they do not create any cooling problem. Engine enclosures on the other hand may generally introduce the maintenance and cooling problems. Maintenance requires at least partial removal of the enclosures. The heat rejection of the exhaust manifold is sufficient to raise the temperature of an insulated, airtight enclosure to a point where the heating hazard is a serious consideration (Kenett, 1990).

In the American Quiet Truck program, the use of total enclosures was rejected in favour of close fitting covers (Cummins NTC-350 engine). Approximately, 3 dB(A) truck chassis, and the underside of the cab sitting over the engine became top of the ventilated engine enclosure, sealed against the belly pan. The cooling fan was moved forward, and the air was ducted through the enclosure. Acoustic insulation (Fibreglass covered with high temperature plastic film) covered the interior of the enclosure. The complete enclosure and cover assembly was found to attenuate noise by acting as a barrier, and it absorbs sound and (almost) removes line - of - sight exposure. Although total noise reduction for the enclosure system was not measured, the quiet truck can achieve noise levels as low as 72 dB(A), and the engine noise was estimated to be 69-70 dB(A).

A technique to reduce the air borne noise emanating from the structure of engines had been investigated by the Deutz engine company (Anon, 1990). The technique applied to FL1011 engine block and a crank case was involved such measures as the use of very stiff support for the crank case bearing housings, a reinforced injection pump mounting, and reinforcing the lower deck of the casting to which the sump is attached.

A different approach to the problem was investigated by Dr.Takashi Suzuki of the Hino Motors in Japan (Kenett, 1990). His method was to cut-away the buttresses between the crank bearing housings and the crank case walls, so that the crank vibrations are not transmitted to the crank case walls.

Finite element method was used to measure the vibrational behaviour of the engine block and the crank case. This method indicates that, without complete redesign, it is difficult to gain a higher noise reduction.

Most of the European truck manufacturers have been obliged to supply vehicles to meet an 80 dB(A) limit. Typical add-ons include acoustic shielding at the sides of the engine, shields for the sump and the rear end of the engine, covers for the engine top and exhaust down pipe. However it is easy to misfit them or leave the shielding off altogether. The development of MAN trucks using the cab floor assembly as the lid of a capsule with the inner wheel arches as the capsule sides plus a moulded undershield beneath the sump have largely overcome the above problems.

Various units of a vehicle generate different noise levels due to conversion of energy in them. The engine, transmission, exhaust, body and suspension are the major contributors. In addition, the cooling fan, brakes and the horns emit an operational noise. Table 4.1 shows the noise levels emitted by the different units of an automobile.

4.4 EXHAUST NOISE REDUCTION

Noise reduction involves improved muffling through use of (a) Manifold mufflers; (b) Optimum muffler selection; (c) Duel exhaust mufflers; (d) Wrapping of exhaust mufflers; (e) Vibration isolations between exhaust manifold and exhaust piping.

Mufflers have been shown to be effective and useful devices. There are three basic exhaust configurations used with trucks. They are: (1) horizontal muffler horizontal outlet, (2) horizontal muffler vertical outlet, and (3) vertical muffler vertical outlet. Existing regulations require the vertical muffler vertical outlet system to be used even with light trucks. Horizontal mufflers are short and compact in design. These do require a multi pass design as opposed to the straight through design of vertical mufflers. For a silencer to be effective it requires either a large muffler volume or a smaller volume and highly dissipative components such as back pressure adding devices. Figure 4.1 shows the basic exhaust configurations.

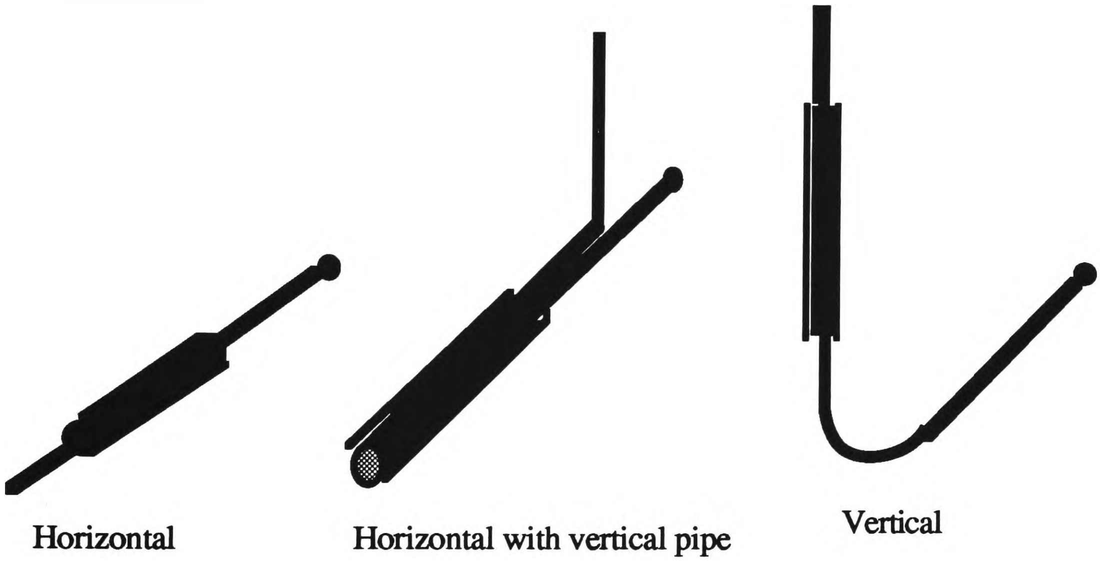


Figure 4.1 Basic exhaust configurations.

Both the naturally aspirated (intake of air due to engine vacuum) and turbo charged (intake of air assisted by either an exhaust driven or mechanically driven pump) engines are used in medium and heavy trucks. These engine types have different noise spectra and hence require different silencing arrangements. Naturally aspirated engines are usually several dB(A) louder than turbo charged engines. Most of the medium size in-service trucks have naturally aspirated engines, and they have a dominant low frequency noise which requires either a larger volume or high back pressure designs to meet the noise reduction objectives. Turbo charged engines have higher exhaust flows due to their turbo efficiency and hence the mufflers can be quite simpler in order to meet the same specific exhaust noise limits.

Although the horizontal muffler system is a cleaner system and it is easy to install, the disadvantage that is a downward directed shorter tail pipe is required, which is less effective for noise control .

The vertical system is the most widely used system in trucks which have 1 to 2 metre tail pipes. Usually the muffler is mounted behind the cab. The exhaust pipes of the vertical system have more bends and they are usually longer than the pipes of the horizontal system. These vertical mufflers can be designed for adequate noise control and low back pressure by utilising straight through designs with minimum dissipative materials. Vertical mufflers are advantageous due to their lower cost, better noise control due to long vertical mounted tail pipe, and their potential for lower back pressure. A disadvantage of this system is the requirement for heavy mounting accessories such as masts, clamps, heat guards etc., and lengthy exhaust piping.

The horizontal system with vertical piping is another muffler system used in light, medium and heavy duty trucks. In this system the muffler is mounted horizontally with a tail pipe running vertically behind the side of the cab. Usually the outlet of the exhaust is located on the opposite side to the inlet. Due to lengthy piping and elbow losses this system has a higher back pressure (Joanne et al., 1990).

4.4.1 Duel Exhaust System

Duel exhaust systems have shown more effective silencing with low back pressure. Due to splitting of the engine's exhaust flow to halves significantly lower back pressures can be obtained. As the back pressure is proportional to flow squared, an exhaust system with half the flow will have one fourth of back pressure (Joanne et al., 1981).

By reducing the size of exhaust pipe whilst maintaining the muffler body size, acoustic impedance mismatch can be changed by changing the area ratio. This increases the potential noise attenuation of a given muffler volume, and it can be properly designed to maintain low back pressure as well. Generally the duel muffler system is required for high capacity engines such as 298 kW (400HP) and above to achieve proper silencing whilst maintaining low back pressure. Figure 4.2 shows the effect of noise attenuation of area ratio of a muffler and exhaust pipe.

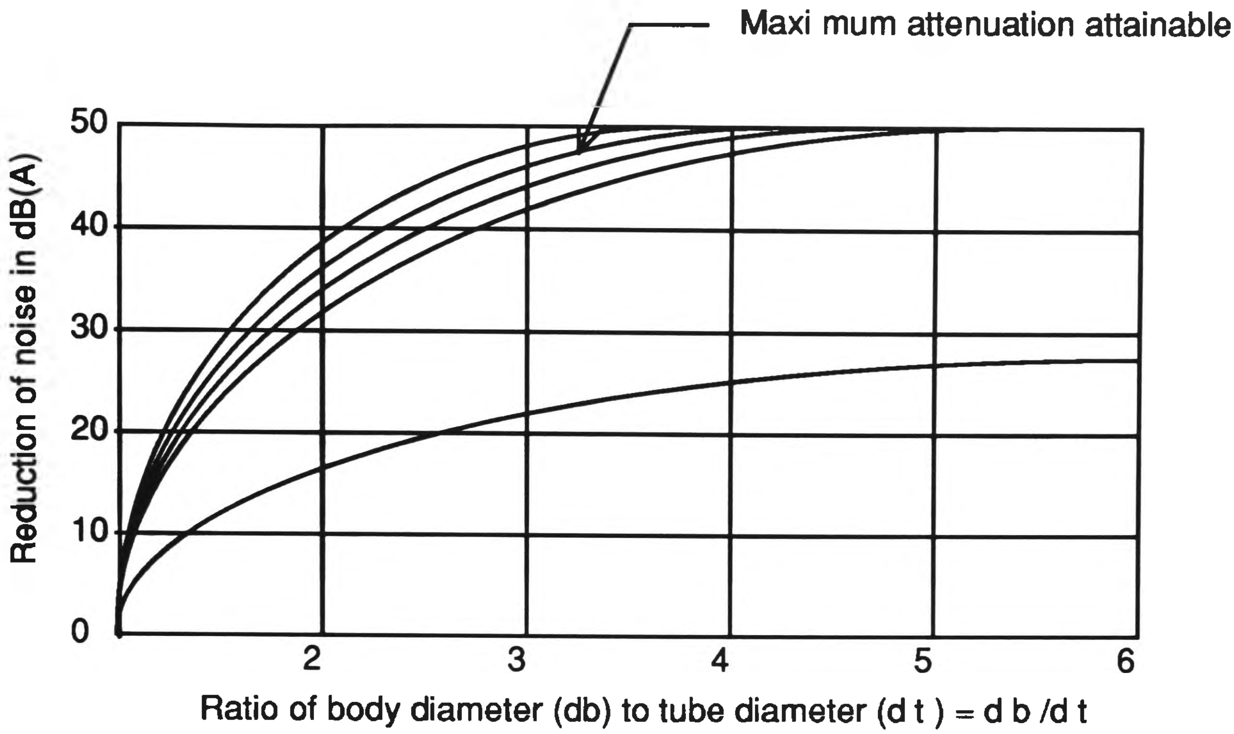


Figure 4.2 Effect of area ratio of a muffler and an exhaust pipe. (After Joanne et al., 1981)

4.4.2 Low Backpressure Exhaust Systems

Special accessories are required in some cases where low backpressure systems have not provided satisfactory silencing effect with particular engines. “T” cans, resonators and stack silencers are widely used in these applications.

Resonators appear to be effective as pre-muffler devices and are located between the engine and the muffler. They add only a very little backpressure due to their straight-through design, and they can provide about 1 to 3 dB(A) noise attenuation.

“T” cans have been found to operate satisfactorily as very small type of a pre-muffler device to replace the common splitter in duel muffler systems. Eventhough the “T” cans add slightly higher backpressure than a conventional splitter, it can provide improved attenuation of about 3 to 6 dB(A). “T” cans may be used with low backpressure mufflers resulting a fuel saving exhaust system.

Stack silencers may be used in place of conventional tail pipes for improved silencing effects. Due to their straight-through design they add no significant backpressure. These stack type silencers provide acoustical packing to provide high frequency noise attenuation. In-line stacks use a nozzle which can provide area reduction inside the stack, as well as packing to provide low and high frequency attenuation. The amount of attenuation provided by a stack type silencer depends on both the engine and the muffler to which it is coupled. Usually this type of silencer can be used more effectively when coupled to less effective mufflers (Joanne et al., 1981).

4.4.3 Mufflers and Backpressure

The backpressure of a muffler can be defined as the static pressure in the exhaust pipes developed downstream of the exhaust manifold or turbo charger. Due to elbows the piping and the flow differences in a typical exhaust system, backpressure cannot always be measured as a fully developed flow. The presence of high pressure acoustic waves in the exhaust system will also affect static pressure readings. Variations in air temperature, barometric pressure and other ambient conditions also affect the engine operation, air flow and exhaust gas temperature, and hence affect the backpressure. However, with specific precautions and conditions, the backpressure can be measured with a reasonable accuracy.

4.4.4 Exhaust Pipes and Backpressure

Whenever better silencing is required, it is necessary to design the exhaust piping to develop low back pressure exhaust systems. A poorly designed exhaust piping arrangement can generate as much as 50% of the maximum back pressure level allowed, and hence will reduce the efficiency of a low backpressure muffler.

The backpressure of an exhaust system can be defined as the sum of the pressure drops (Δ P) across each component of the system.

$$BP = \Delta P_1 + \Delta P_2 + \dots\dots\dots + \Delta P_{exit} \tag{4.1}$$

$$\Delta P_{exit} = \rho \frac{V}{2g} \tag{4.2}$$

(After Joanne. et al., 1980)

where

ρ = density of exhaust gas

V = velocity of exhaust gas

g = acceleration due to gravity

Table 4.2 shows the data related to pressure drop in exhaust systems in heavy vehicles for various pipe and bend diameters.

Table 4.2 Pressure drop data for exhaust systems (After Joanne et al., 1981)

	Outer Diameter 10.16 cm		Outer Diameter 12.7 cm			
Bend Radius-cm	Angle Degrees	Δ P (1) mm Hg	Bend Radius-cm	Angle Degrees	Δ P (2) mm Hg	Δ P (3) mm Hg
10.16	90	35	13.97	90	33	71
11.43	90	30	20.32	90	25	55
13.97	90	27	25.4	90	22	48
20.32	90	25	25.4	45	15	33
20.32	45	15				

4.4.5 Design of Mufflers for Reducing Low Frequency Noise Production Without Increasing Backpressure

Typical mufflers designed for vehicles utilise radial flow components to obtain efficient silencing. This system achieves the silencing effect by energy dissipation in a highly turbulent flow components. Another typical approach is to use straight-through axial flow components to minimise flow losses. This system is frequently used in low backpressure mufflers and used as branch resonators as well. As this device relies more upon reactive silencing than dissipative silencing, its performance depends on its location in the exhaust system. Figure 4.3 (a) shows the radial flow type, and Figure 4.3 (b) shows the axial flow type.

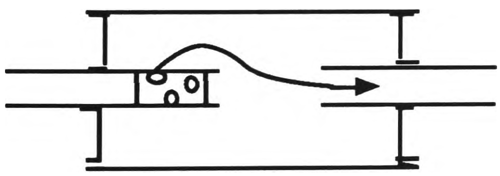


Figure 4.3 (a) Radial flow type

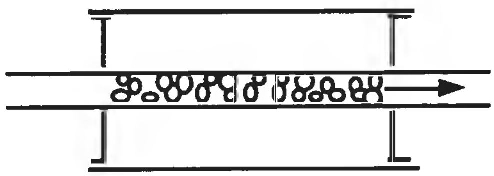


Figure 4.3 (b) Axial flow type

Eminox silencer systems in England have successfully used a number of methods including the slots in the perforated inner muffler pipes instead of holes, breaking the pipe inside the silencer so that there is a gap between the two pieces, and flaring the ends of the inner pipes to dampen the exit turbulence. Figure 4.4 shows a combination of perforated straight-through pipes in expansion boxes and a triple pass baffle compartment silencer arrangement required to mitigate the exhaust noise towards 84 dB(A) for trucks by suppressing low frequencies.

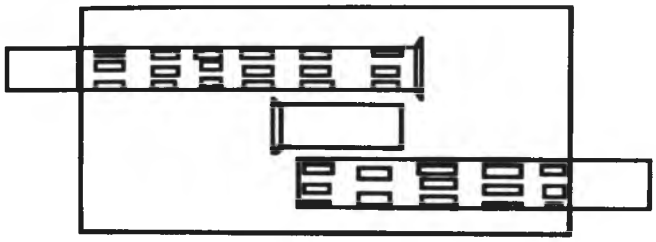


Figure 4.4 Combination of perforated straight-through pipes in expansion boxes

Reducing low frequencies without raising the backpressure may be done by introducing a break in the flow pipes with three separate expansion chambers of differing sizes. Figure 4.5 shows this design possibility (Transport Engineer, 1990).

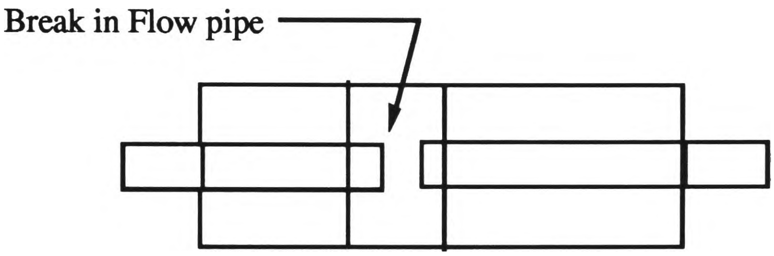


Figure 4.5 Design with break in flow pipes and expansion chambers of different sizes.

4.5 INTAKE NOISE REDUCTION

Auxiliary intake mufflers or acoustically treated ducts to the passenger compartment (the latter being the most desirable from the stand point of reducing the noise level without degrading the engine performance) can yield upto 6 dB(A) noise reduction so that the intake noise of a non freight liner quiet truck may be around 62 dB(A).

4.6 TYRE NOISE REDUCTION

Tyre noise reduction is essentially a tyre tread- roadway surface selection. Barring an unanticipated technical breakthrough in tyre noise reduction methods, noise reduction for existing highways is a matter of tread selection. Data presented in table (2.3) shows that the use of a neutral rib and the ribbed tyre treads effect noise reductions of about 4.5-6 dB(A).

According to Dr. Hochrainer of Semperit Tyres Limited (Kenett, 1990), Semperit tyres had done some important work on tyre noise reduction. One influence discovered was the tyre pressure. Noise tests were normally done with the truck's tyres at normal laden working pressure, typically 6.0 to 7.5 bar. If the pressure is reduced to a level that is appropriate for the laden vehicle (as tested, typically 1.8 to 2.0 bar), then the tyre noise element was reduced by 4 dB(A).

A parallel result emerged when the testing was done for a fully laden vehicle with correctly adjusted pressures, and it had been found that the noise level was consistently lower than the over inflated tyres.

4.7 TRANSMISSION NOISE REDUCTION

In quiet vehicle design, the transmission noise could become a problem in producing as much as 15 dB(A) levels. Enclosures are simple and effective means of achieving noise reductions sufficient for quiet truck.

The following reductions of noise levels are expected as a result of proposed improvements of vehicle technology. A big West German Gear Box manufacturer, ZF Limited had designed a gear box called ZF8S-180 to cover the torque range of 1200 upto 2000 N / m (Anon, 1989). This is a synchromesh gear box which incorporates an epicyclic range and has short shafts revolving in large taper roller bearings at either side, and therefore naturally stiffer, and this together with subtle improvements in tooth profiles and machining accuracy on the helical gears, has reduced transmission noise by 4 dB compared with older model gear boxes.

4.8 FIELD EXPERIMENTATION IN SEARCH OF TRAFFIC NOISE MITIGATION AT SOURCE

The field research work as part of this thesis was conducted in the Wollongong area of the Illawarra region of New South Wales, during months of October, November and December - 1991, at Mount Ousley road - F6 Freeway, Burelli street, Keira street, Crown street, North field avenue, Flinders street - Princess highway, and Spring hill road - Wollongong at selected seven test sites. Speed surveys, traffic counts, community noise surveys, drive-by traffic noise level surveys (general), drive-by noise level surveys (individual), tyre/road interface surveys, load noise relationship surveys, and engine speed-noise level relationship surveys were done to predict the effectiveness of use of different types of tyres, various road surfaces, vehicle speeds on vehicle noise levels, and to predict the adverse effects of excessive loading and excessive acceleration on traffic noise levels. Two main surveys were the tyre/surface interface survey and the vehicle drive-by noise level survey. The vehicle drive-by noise surveys were conducted and the total traffic noise levels were recorded, whilst the peak noise levels of individual vehicles were noted separately for classification of noise levels according to different classes of vehicles.

4.8.1 Instrumentation and Test Procedure for Vehicle Drive - by Noise Tests and Vehicle Speed Surveys

Traffic noise level data was collected between 06.00 and 24.00 hours of each day of survey, at distances of 17.5 meters from the median line of the subjected arterial roads, for a duration of 10 minutes for each hour, by using the Precision Noise Level Meter (B & K 2215), and a FM Stereo Tape Recorder (B&K type 7003). The noise level meter, noise level analyser, and the tape recorder have been checked for the charge level of the batteries. The noise level meter which was calibrated by using the pistonphone (B & K 4230) was mounted on a tripod and was connected to the tape recorder(Reference pp 208 of Appendix 3). Noise levels were recorded and analysed for every 0.1 second over a 10 minute sampling period in each hour by using the Community Noise Level Analyser (B & K 4426). Automated - Streeter Amet (iii) Traffic computer was used for automatic traffic counting (Reference pp 200 of Appendix 1). Manual traffic counting was done in order to obtain the percentage of heavy vehicles. Kustom's KR 11 Moving Radar type vehicle speed detection system was used to detect the vehicle speeds (Reference pp 208 of Appendix 3).

Figure 4.6 shows a map of all the experimental sites.

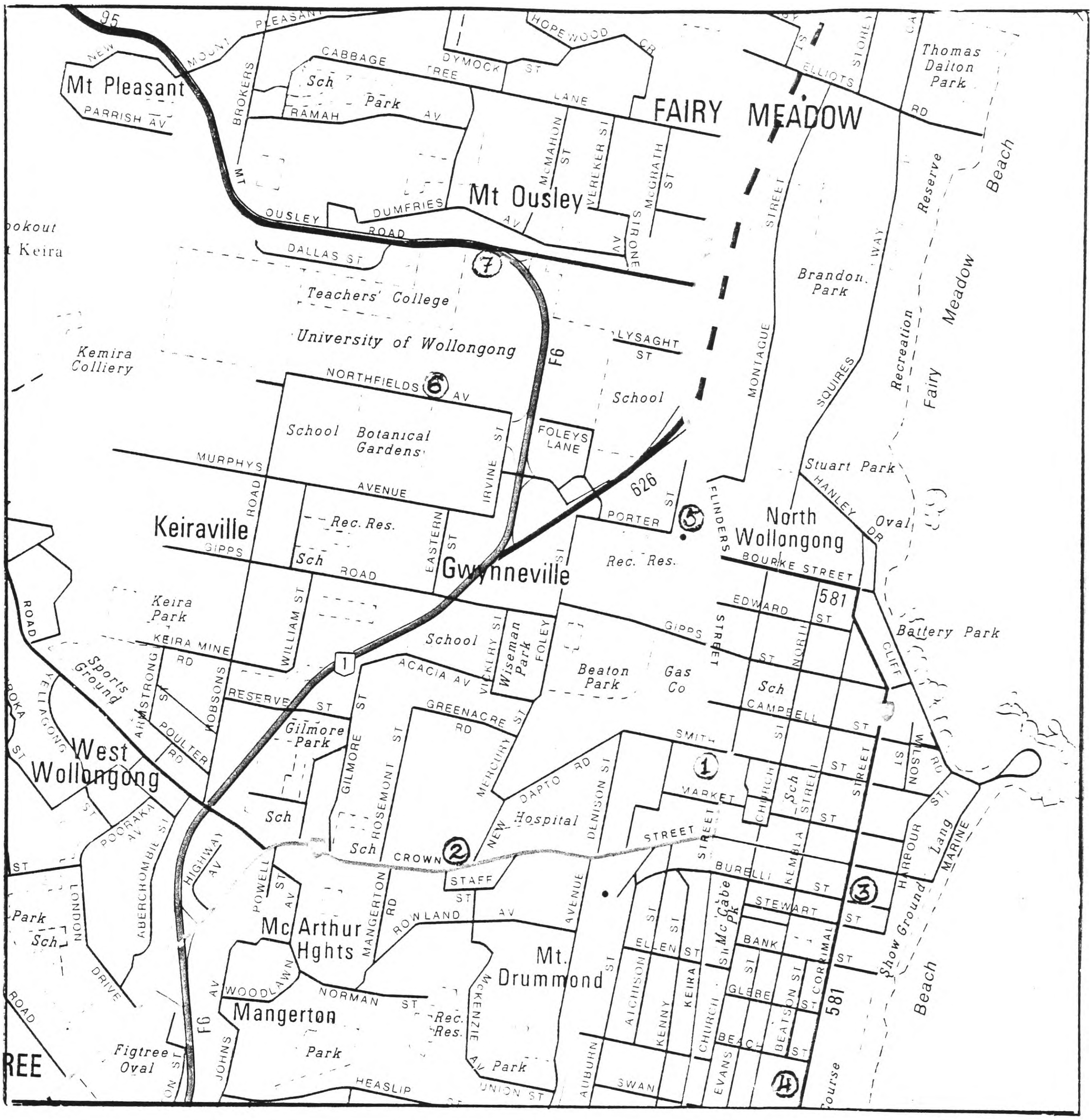


Figure 4.6 Map of experimental sites

For the purposes of recording speed, traffic count, and noise level measurement, the following vehicle classes which were both north and south bound selected were:

1. private vehicles (cars, station wagons, panel vans and pick-ups)
2. light commercial vehicles and light buses.
3. medium commercial vehicles.
4. heavy commercial vehicles (Rigid)
5. heavy commercial vehicles including trailers, semitrailers and heavy buses
6. motor cycles.

The recordings were taken by using the above mentioned instruments. Real narrow band analysis was used to overcome the Doffler Effect frequency shifts as the vehicle passes. The repeatability of pass by noise levels was investigated simultaneously with 50 repeat passes for the real time frequency analysis. The standard deviation of the individual pass-by sound levels about the linear regression line with the logarithm of the speed was 0.57 dB(A), thus giving a standard error of the mean of 0.23 dB(A) for 6 passes and 0.18 dB(A) for 10 passes. Table 4.3 shows the data related to the survey done at site number 1 (F 6 Freeway- Mount Ousley road - opposite to Illawarra Technology Centre behind University of Wollongong).

4.9 INDIVIDUAL VEHICLE SPEED SURVEYS

The individual vehicle speed surveys were conducted at site-1 as a supportive study, and the speeds of both the north bound and south bound vehicles were recorded by using the radar speed recorder (Reference Appendix 3). This survey was done parallel to the noise level recordings. Figure 4.7 (a) and (b) show consecutively the results of the speed survey of the north and south bound vehicles at site no 1 (Flinders street - Princess highway, Wollongong).

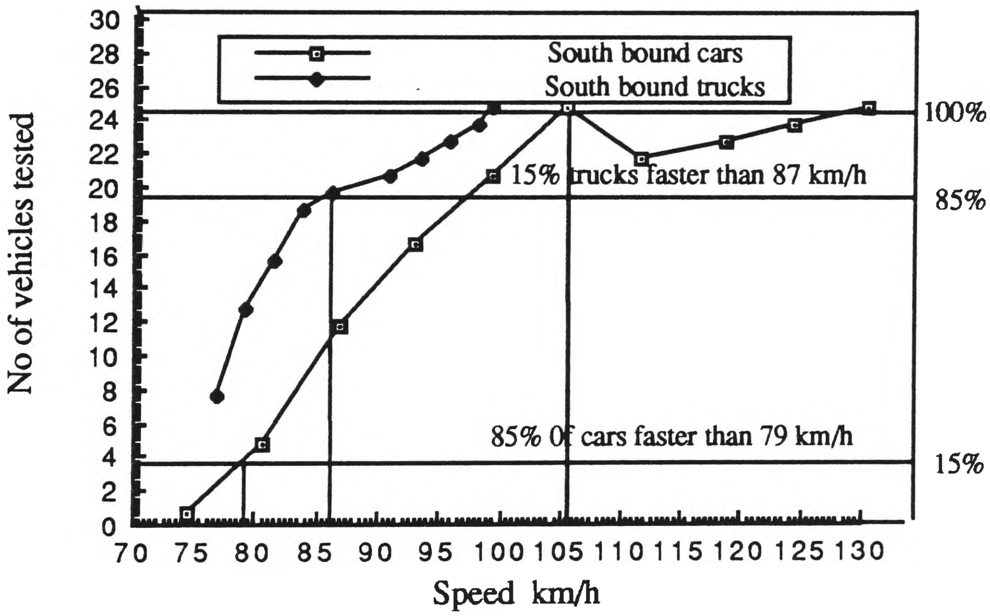


Figure 4.7 (a) Results of the speed survey - south bound traffic

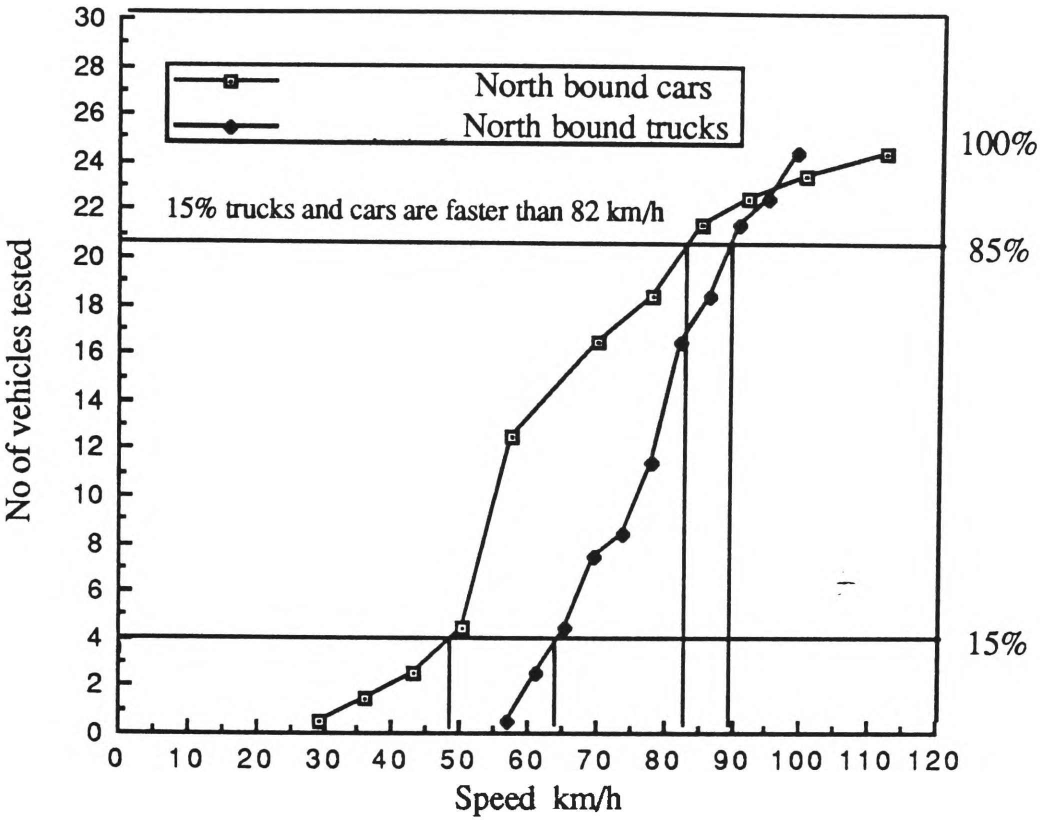


Figure 4.7 (b) Results of speed survey - north bound traffic

Kustom KR 11 radar type vehicle speed measuring equipment was used to measure the speeds of both the north and south bound vehicles. Using the statistical package integrated to Kustom KR 11, the mean speed for samples of cars and trucks was separately calculated for each direction. The standard deviation of vehicle speed was calculated and the 85th percentile speed determined for each group of vehicles. Accordingly, cumulative frequency graph was plotted for each group of vehicles. 85th percentile speed is the speed below which 85% of the vehicles are being driven, and this speed is significant since it is often used to set the upper limit for particular roads. The mean speed was also determined from the spot speed survey. A note of the percentage of vehicles travelling faster than the speed limit also was made.

4.10 VEHICLE DRIVE - BY NOISE SURVEY

The objective of the survey is to investigate the data regarding the traffic noise levels, traffic speed and traffic flow strength, for vehicle classifications such as light cars and allied vehicles, medium Trucks, and the Heavy duty Trucks; Eg: >3 axle types. Traffic noise levels were detected by using the Precision Noise Level Meter B&K 2215, which was connected to a FM Stereo Tape Recorder (B&K 7003) for recording the noise levels. Both the tape recorder and the noise level meter have been checked for the charge level of the batteries prior to the measurement exercise. The noise level meter was set on a tripod at a height of 1.2 meters above the ground level has been calibrated by using a pistonphone (B&K 4230). A foam wind shield was used for wind protection of microphone of the noise level meter. Manual traffic counts were taken to detect the percentage of heavy vehicles and in addition, vehicle speeds were detected by using Kustom's KR 11 Radar vehicle speed detector, and flow levels data was obtained by using the automated traffic computer - Streeter Amet (iii). The recorded noise levels were analysed by using the Community Noise Analyser (B&K 4426). Drive - by noise level surveys were conducted in two stages. The first one was the general drive - by noise survey, and the second one was individual drive - by noise survey. In doing these surveys, the following facts had been considered.

- The sound pressure decreases according to the inverse square law as the area to be influenced increases. The spreading effect dominates sound attenuation for distances over 300 metres. The radiating sound waves from traffic usually takes about 2-3 metres to settle down to a well defined periodic form. Appreciable attenuation effects within about 10 metres (Lay, 1985).

- NAASRA (1980) indicates that the measurement position should be located at or within the boundaries of the selected site, as close as practicable to the place and the time of the public annoyance.
  It also recommends that the measurement position should be at least five metres from the nearside traffic lane (Taylor and Young, 1988)

- Majority of the residential amenities influenced by traffic in urban Australia are located between 10 to 20 metre distance from the edge of the near side traffic lane.

The Figure 4.8 shows the number of dwelling units located near the side of the arterial roads according to the distance from the edge of the arterial roads in North Wollongong, plotted as per the data obtained from Wollongong City Council. It clearly shows that most of the residential dwellings are located within 10 to 20 metres from the edge of the arterial roads.

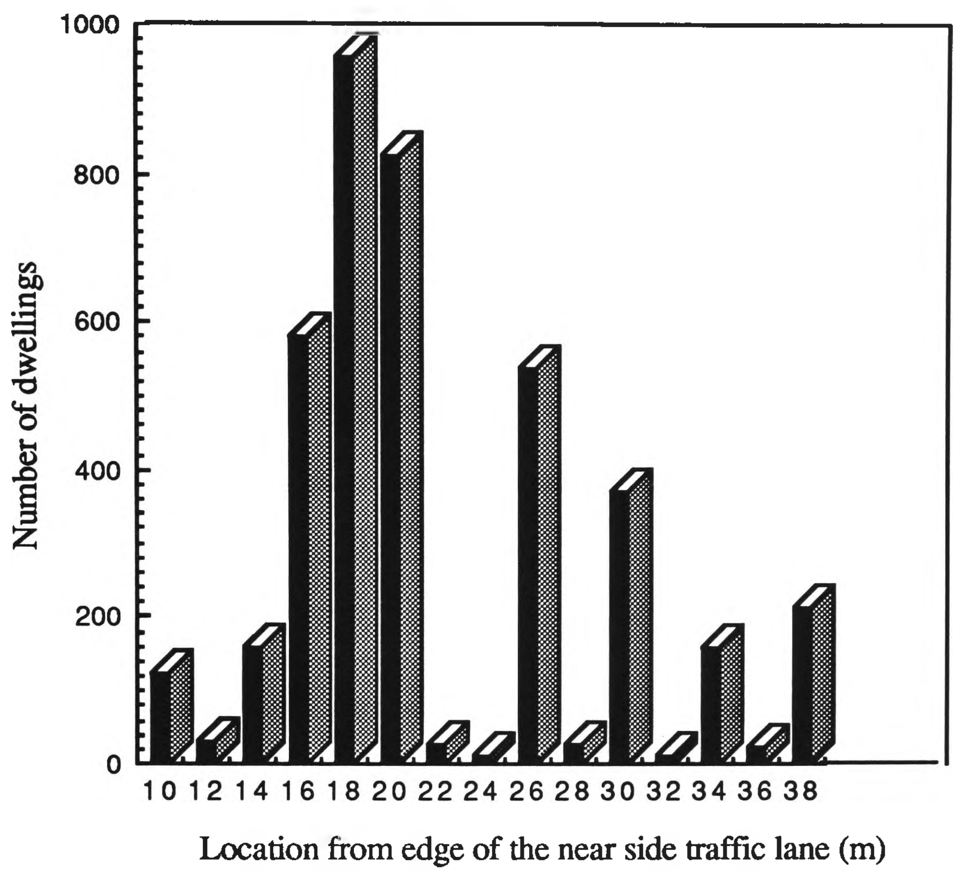


Figure 4.8 Number of dwellings located near the arterial roads in North Wollongong

o According to arterial road set up in Australia, majority of the arterial roads either 4 or 6 lane 2 way type and each lane is 3.5 metres wide. Majority of them are consisted of a median strip of at least 1 metre wide. The noise influence of moving traffic in both the north and south bound directions is perceived by the receiver and hence, the observation distance of 7.5 metres as used by the other researchers does not give a correct indication of the noise level. Hence the author of this thesis proposes that the observation point should be at 17.5 metres distance from the centre line of the median strip of road as follows:

Width of 2 lanes of 3.5 metres each	= 3.5 X 2
	= 7 m
1/2 width of the median strip	= 1 X 1/2
	= 1/2 m
10 metres from the edge of the near side traffic lane	= 10 m

Total distance from source to observation point = 17.5m

Figure 4.9 shows the traffic noise levels calculated using the Burgess formula, keeping traffic flow level as 2000 veh/h, mean speed as 80 km/h, and the percentage of heavy vehicles as 10%. In Figure 4.9, the above variables are kept constant and the measurement distance (d) is varied. Mean traffic noise level lies within the closest range of 17.5 metre distance and hence it has been decided to select 17.5 metre from the centre line of the median strip as the noise measurement point, and accordingly the measurement distance d was kept as a constant.

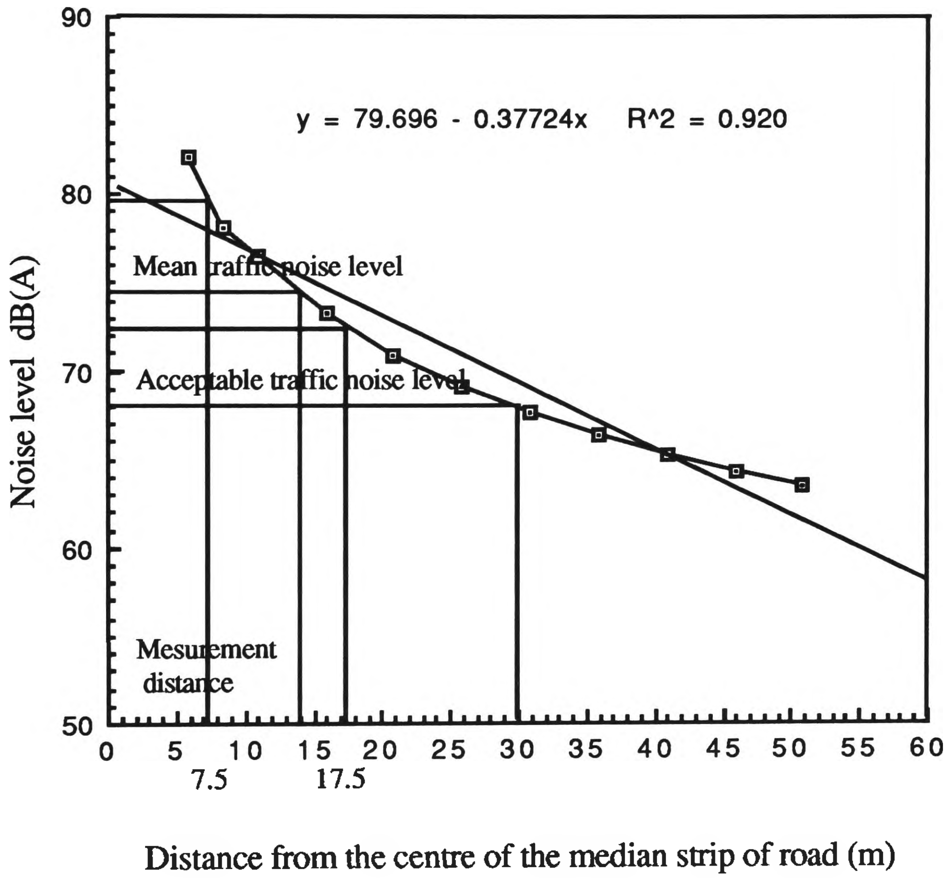


Figure 4.9 Noise attenuation over the distance

The regression equation was fitted to the above Figure was as follows:

$$y = 79.696 - 0.37724\,x \quad (4.3)$$

It may be used to calculate the distance correction after the application of the proposed regression model of the author for the calculation of road traffic noise to suit with the Australian traffic environment.

4.11 RESULTS OF DRIVE - BY NOISE SURVEY (GENERAL)

Table 4.3 (a) shows the field measurements taken at Flinders Street, Wollongong (site no: 1), and the Table 4.3 (b) show the results of the regression analysis for the same results.

Table 4.3 (a) Free field traffic noise levels - 1.2 meters above ground at site no: 1

Flinders Street	06.00-24.00	31-Oct-91	Site 1	
Observation	Flow	Mean Speed	% H.V.	Noise level
1	608	90.5	8.5	76.5
2	634	80.4	9.8	74.9
3	772	75.3	14.1	82.3
4	1192	70	15.3	84.2
5	1091	88	11.4	87.4
6	1110	90.2	15.9	90.7
7	1174	78.7	14.6	88.3
8	1070	80.2	12.6	79.6
9	1358	82.5	12.9	86.4
10	1501	84.2	15	88.9
11	1481	79.5	9.5	79.9
12	1346	78	7.3	80.1
13	830	89	5	69.7
14	673	78.5	3.9	68.8
15	537	76.4	13.5	81.2
16	401	81.5	16.4	89.3
17	438	83.2	15.2	91.3
18	326	75.4	13.9	84.6

Table 4.3 (b) Results of the regression analysis for the measurements of site no: 1

Regression Output		Site 1	
Constant		40.538638399	
Std Err of Y Est		2.8461557633	
R squared		0.8545943152	
No. of Observations		18	
Degrees of Freedom		14	
	Flow	Speed	% H.V.
X Coefficients	0.0029279978	0.2386206464	1.6630609622
Std Err of Coef.	0.0017931108	0.1255575347	0.1860505743
t-statistic	1.6329152095	1.9004884649	8.9387574756

Table 4.4 (a) show the traffic noise level data related to drive-by noise surveys conducted at Mount Ousley Road - Wollongong (site no: 2), and Figure 4.4 (b) shows the results of the regression analysis for the same measurements.

Table 4.4 (a) Free field traffic noise levels at 1.2 meters above ground level at site no: 2

Mt Ousley Road		06.00-24.00	24-Oct-91	Site 2
Observation	Flow	Mean Speed	% H.V.	Noise Level
1	140	80.5	6.8	61.3
2	614	79.8	8.8	69.7
3	936	86.4	3.9	62.9
4	1435	89.5	14.3	90.5
5	1197	70.2	4.9	60.6
6	1158	75.3	8.8	71.2
7	1193	90.4	13.6	89.3
8	1343	87.9	14.2	92.2
9	1190	82.4	12.5	87.8
10	1314	75.1	11	80.4
11	1277	76.3	10.7	80.6
12	1405	91.5	14.3	88.7
13	1249	84.3	12.6	87.4
14	811	89.2	13.4	90.1
15	776	87.6	9.8	85.3
16	574	86.5	2.3	63.6
17	489	79.4	2.5	60.3
18	577	80.6	1.6	62.5

Figure 4.4 (b) Results of the regression analysis for the measurements of site no:2

Regression Output		Site 2	
Constant		14.43710854	
Std Err of Y Est		3.6419083765	
R squared		0.9302193474	
No. of Observations		18	
Degrees of Freedom		14	
	Flow	Speed	% H.V.
X Coefficients	0.004777144	0.4667018394	2.0683064897
Std Err of Coef.	0.0033150411	0.1672185859	0.3083984259
t-statistic	1.4410512146	2.7909687003	6.7066052103

4.12 ANALYSIS OF DRIVE - BY NOISE LEVEL SURVEY (GENERAL) RESULTS

It is assumed here that the drive-by noise level is a function of the speed, flow, and percentage of heavy vehicles only. The distance from the noise source to the observation point was kept constant (at 17.5 m) as per the discussion given in section 4.10. Evaluation of the results of the drive - by noise levels was done using the following basic regression model.

$$DNL = f(\alpha, \beta V, \rho T, \gamma S) \qquad (4.4)$$

where

DNL = Drive - by noise level
V = Vehicle flow
T = Percentage of heavy vehicles
S = Mean speed (km/h)
d = Distance from the median of the road to observer point
θ = Constant for distant correction
α = Intercept and
β, γ, ρ, = Regression Coefficients.

Among the above variables, the mean vehicle speed, percentage of heavy vehicles, and the traffic flow levels have been found significant by some of the previous researchers. Burgess has not considered the significance of the speed noting that it is difficult to be measured in urban areas (Lawrence and Burgess, 1975). UK DoE model has not considered the measurement of distance (d). Ontario model has considered the speed of heavy and light vehicles separately. It was very clear that non of them has predicts the traffic noise levels prevail in urban Australia. Hence, in his research the author has paid his attention to all the above variables keeping the distance as a constant and researched to develop a suitable model for the calculation of road traffic noise to suit the Australian traffic environment.

The following four regression equations are the available widely used models for traffic noise prediction and measurements. They were namely; DoE (UK), Burgess (University of New South Wales), Ontario (Canada), and Delany's. .

1 DoE - UK, 1975.

$$L_{10} = -27.6 + 10\log Q + 33\log\left(V + 40 + \frac{500}{V}\right) + 10\log\left(1 + 5\frac{T}{V}\right) \qquad (4.5)$$

2 Burgess - University of New South Wales, 1977

$$L_{10} = 56 + 10.7 \log Q + 0.3T - 18.5 \log d \qquad (4.6)$$

3 Ontario - Ministry of Transport and Communication - Canada, 1976

$$L_{10} = 52.4 + 11.2 \log (Q_c + 3\,QT) - 16 \log d + 0.21\,V \qquad (4.7)$$

4 Delany - National Physical Laboratory - UK, 1972

$$L_{10} = K_1 + A_1 \log Q + B_1 \log S + C_1 T - D_1 \log d \qquad (4.8)$$

Where

$K_1 = 31$, $A_1 = 8.9$, $B_1 = 16.2$, $C_1 = 0.117$, $D_1 = 14.7$

Where

V = Average speed of vehicles
T = Percentage of heavy vehicles
d = Distance from centre of flow of nearside lane
Q = Total traffic volume per hour
Q_c = Volume of light vehicles
Q_t = Volume of heavy vehicles

As per table 4.3 (b) the t-statistic of regression results show that the percentage of heavy vehicles was highly significant at 1% level of probability. But the speed and the flow were not significant. The regression model for the site no:1 shows a variability of 85% explained by percentage of heavy vehicles, speed and the flow variables.

According to the significance of the coefficients, the following regression model is proposed for the site no:1.

$$DNL = 40.538638369 + 0.0029279978\,Q + 0.2386206464\,V + 1.6630609622\,T \qquad (4.9)$$

Where

V = Average speed of vehicles
T = Percentage of heavy vehicles
Q = Total traffic volume per hour
DNL = Drive - by noise level

A distance correction can be applied by deducting the value of "d" as found by application of equation (4.2) as per Figure 4.10.

Table 4.4 (b) shows the regression results for the site no: 2. Coefficients show that the percentage of heavy vehicles was highly significant and the speed also was significant at 1% level of probability. The was not significant here. A good variability of 93% for all the three variables is found. According to the significance of the coefficients, the following regression model is proposed for the site no: 2.

$$\text{DNL} = 14.437310854 + 0.004777144\ Q + 0.4667018394\ V + 2.0683064897\ T \tag{4.10}$$

As per the regression results given in appendix 2 for site no: 3, the coefficients show that the percentage of heavy vehicles and the speed levels were significant, but the flow was not significant at all (negative significance). this may be due to the large number of heavy vehicles flowing on this road other than the cars. Here the flow levels were lower than the other sites. Most of the heavy vehicles bound to the coal loader and the Spring Hill steel (BHP) Mills have influenced this situation. A reasonable variability of 76% was found for all the three variables.

Regression results for site no: 4 as per the appendix 2, show with the coefficients that the speed and the percentage of heavy vehicles at this site were not that significant as seen in the previous sites. The significant can be described only at 0.5% probability level only. The flow was not significant even at 0.5% level. Percentage of heavy vehicles and the speed were comparatively less on this road, and it may be a reason for this result. A low level of variability of 67% was found with the regression result for all the three variables. The following regression equation is proposed for the site no: 3.

$$\text{DNL} = 29.039582534 + 0.0063677853\ Q + 0.3963559613\ V + 0.8783092764\ T \tag{4.11}$$

Regression results for the site no: 5 as per appendix 2, show that the percentage of heavy vehicles and the flow level were significant at 1% of the probability level at this site. But the speed was not significant. Stop - start conditions, and the slow speeds at traffic light might have influenced this situation. Being the central shopping area of the city, the capacity of the flow is high along this road almost at saturation level and it might be a prime factor which has contributed the significance of the flow. a very high level variability of 93 % for all the three variables has been noticed. According to the coefficients, the following regression model is proposed for the site no: 5.

$$\text{DNL} = 44.67521476 + 0.0170620126\ Q + 0.1258309587\ V + 0.9374818723\ T \tag{4.12}$$

Regression result for the site no: 6 as per appendix 2, show that the significance of the percentage of heavy vehicles at 1% of the probability level was very high here. The high magnitude of the coefficients show that the importance of the percentage of heavy vehicle to the traffic noise levels. The speed has shown a negative significance. Stop start conditions due to the presence of traffic lights, might have influenced the speed levels. The flow also is not significant here. A high variability of 94 % for the noise level seen against all the three variables.According to the coefficients, the following regression equation is proposed for the site no: 6.

$$DNL = 64.971558419 + 0.0014146099\,Q + (-0.148525114)\,V + 2.4927242155\,T \qquad (4.13)$$

Regression results of site no: 7 as per the appendix 2, show that the percentage of heavy vehicles was significant at 1% of the probability level, and the speed was significant at 0.5% of the probability level. But the flow level has a negligible significance. A good variability of the noise level of 88% over all the three variables was found. The magnitude of the coefficients show the high influence of the percentage of heavy vehicles, for the higher noise levels. According to the coefficients, the following regression model si proposed for the prediction of traffic noise levels at site no: 7.

$$DNL = 36.495111583 + 0.0001287736\,Q + 0.3111077285\,V + 1.9536960039\,T \qquad (4.14)$$

Site influences were accounted for by including 6 binary dummy variables for sites 1 to 6. these dummies are: $Site_1$ (1 for site 1, 0 for all others), $Site_2$ (1 for site 2, 0 for all others), $Site_3$ (1 for site 3, 0 for all others), $Site_4$ (1 for site 4, 0 for all others), $Site_5$ (1 for site 5, 0 for all others), $Site_6$ (1 for site 6, 0 for all others), $Site_7$ (1 for site 7, 0 for all others).

According to the regression results obtained using the above binary dummy variable method as per appendix 2, the following regression equation is estimated for the pooled data to be applicable to the Illawarra region of New South Wales.

$$\begin{aligned} DNL = {} & 31.005797 + \underset{(2.4359)^*}{0.003204\,Q} + \underset{(6.2598)^*}{0.3725814914\,V} + \underset{(14.7788)^*}{1.758374557\,T} \\ & - \underset{(1.6936)}{2.70559\,Site_1} - \underset{(2.7505)^*}{4.336419\,Site_2} - \underset{(2.5788)^*}{4.17827\,Site_3} - \underset{(2.8895)^*}{4.570047\,Site_4} \\ & - \underset{(1.7012)}{2.607795\,Site_5} - \underset{(3.4344)^*}{5.24441\,Site_6} \qquad (4.15) \end{aligned}$$

(* Significant at 1% level of probability.)

The model shows that the flow, speed, percentage of heavy vehicles and site dummies explain over 82% of the variability of the noise level. Flow, speed and percentage of heavy vehicles are all positively and significantly influencing the level of noise. The percentage of heavy vehicles seem to have a greater influence on the traffic noise level than the flow of vehicles or the speed of vehicles (14.7788 > 6.2598 > 2.4359)* . Speed variable also is highly significant. Sites 2, 3, 4 and 6 contribute to the noise level than sites 1 or 5.(Because of the binary nature of dummy variables, the sign of the coefficients are disregarded.)

To develop a general traffic noise prediction model the dummy variables were removed to remove the site effect by multiplying the site variables by 1. Then the sum of the site coefficients was subtracted from the intercept to find the common intercept.

Sum of the site variables	= 23.642214
Intercept	= 31.005797
31.005797 - 23.642214	= 7.363583

According to the coefficients the proposed general traffic noise prediction model as more appropriate for the Illawarra region of New South Wales is as follows.

$$DNL = 7.3636 + 0.003204\,Q + 0.372581\,V + 1.75583\,T \quad dB(A) \quad (4.16)$$

The distance correction can be deducted as per equation 4.2.

4.13 RESULTS AND ANALYSIS OF INDIVIDUAL DRIVE - BY NOISE LEVEL SURVEY

Summary of the results of individual drive - by noise level survey was conducted at Flinders Street - Princess Highway, Wollongong (site 1) is presented according to different vehicle types in Table 4.5.

Table 4.5 Summary of average vehicle peak noise levels of individual vehicles measured separately.

Vehicle Type	Sample Size	Percentage of Heavy Vehicles	Mean Speed	Standard Deviation Speed	Mean Noise Level	Standard Deviation Noise Level
C (PC)	3534	0	92.1	6.7	68.7	5.1
C (LT)	675	0	89	7.1	64.6	4.1
HGV (MT)	320	4.21	86	6.9	78.2	4.3
HGV(R)	1022	13.44	93	6.1	85.7	3.7
HGV(A)	25	0.32	88	8.4	84 .8	3.4
HGV(B)	73	0.96	82.24	5.5	77.4	3.9
HGV(MC)	51	0.76	92.16	4.4	86.1	2.8

Legend: C (PC) = Private cars, station wagons, pick-ups
C (LT) = Light trucks, light buses
HGV (MT) = Medium trucks, medium buses
HGV (R) = Heavy rigid trucks
HGV (B) = Heavy rigid buses
HGV (T) = Heavy Trailers and semitrailers with prime movers
HGV (MC) = Motor cycles

For the evaluation of peak drive - by noise levels were measured at 17.5 meters from the centre line of the road surface where the noise tested vehicles were flowing. In this thesis, these noise levels referred to peak noise levels. The individual noise levels from random samples of different types of vehicles were noted separately whilst the total noise level generated due to traffic was recorded by using the tape recorder for analysis of general noise samples. The mean and standard deviation values for these peak levels were calculated.

According to the above results obtained by using the above four regression equations given in page 111 and 112, it appears that none of them predicts the actual L_{10} value recorded according to existing traffic environment in Australia. Hence the author of this thesis for the calculations applicable to this thesis has developed a traffic noise prediction model (equation 4.16) according to his findings during his drive-by noise level surveys, conducted at seven sites covering an area of about 50 square kilometres in the Illawarra region of New South Wales. The results of the drive-by noise surveys have been given in appendix 2.

Table 4.6 shows the predicted traffic noise level calculated using the UK DoE regression model for different types of vehicles.

Table 4.6 Predicted noise levels

Vehicle Type	Predicted Noise level - dB(A)
Car	70.86
Light Truck	63.27
Medium Truck	61.07
Heavy Truck - Rigid	69.23
Heavy Truck - Trailer	48.05
Bus	53.22
Motor cycle	51.50

Table 4.5 above shows the significance of the speed and the noise levels of the trucks compared to the speed and the noise levels of cars. Eventhough the standard deviation of the speed of cars is 6.9, the standard deviation of noise levels for cars is only 2.04, where as the standard deviation of the truck speed is comparatively less (3.78), the standard deviation of noise levels for the trucks is 5.07. This shows the urgency of the requirement of mitigating truck noise levels. It is clearly seen from these results that immediate action needs to be taken to reduce the high speed levels of truck operation, if the authorities are concerned about people and their health in the area affected by increasing levels of traffic noise. If action can be taken to reduce both the truck and car speed levels, the prevailing noise levels can be reduced reasonably. Unless immediate measures will be taken to mitigate the excessive truck noise levels about 14.44 dB(A) above the acceptable traffic noise level [68 dB(A)], the authorities might have to pay millions of Dollars as compensations on medical grounds to the residents living in close proximity to arterial roads if they file legal action. The other alternative available is to make arrangements to safeguard them by building the earth mound or vertical timber paling or corrugated Aluminium type noise barriers at the expense of the government.

Table 4.7 shows the relationship of different individual vehicle types to the traffic noise. In column three of the table, the vehicle classification is shown, where as cars (C) and light trucks (LT) have been further grouped into the category of cars and the others such as medium trucks (MT), rigid trucks (HGV-R), articulated trucks (HGV-T), buses (HGV- B), and the motor cycles (HGV-MC) can be categorised into the category of trucks.

Table 4.7 Noise levels recorded from 40 individual vehicle drive-by test at site no:3

EVENT NUMBER	NOISE LEVEL	SPEED km/h	VEHICLE TYPE
	dB(A)		
1	69.5	53.3	LT
2	67.4	55.8	C
3	72.4	68	C
4	80.1	54	C
5	73.3	-	HGV(T)
6	80.8	70.5	LT
7	68.9	88.8	HGV(R)
8	82.9	76.2	HGV(T)
9	82.6	86.4	C
10	72.9	77.3	C
11	73.4	62.5	C
12	69.1	60.3	C
13	68.3	85.1	HGV(T)
14	80.7	76.4	HGV(T)
15	70.1	70.2	C
16	74	64.7	LT
17	69.6	62.1	C
18	67.8	68.5	C
19	69.6	62.9	C
20	65.6	64	C
21	64.9	70.2	C
22	71.7	63	LT
23	69.5	89.4	HGV(R)
24	84.5	59.2	C
25	65.6	58.7	C
26	64.8	66.6	C
27	88.9	101.4	HGV(MC)
28	69.4	60	HGV(B)
29	69.2	69.4	MT
30	82.7	58.3	MT
31	65.4	58.4	C
32	68.7	57	LT
33	68.9	-	C

34	65.2	-	C
35	67.1	52	C
36	70.5	71.3	HGV(B)
37	68.4	66	C
38	67.1	65.8	C
39	66.9	64.2	HGV(T)
40	68.9	-	LT

4.14 ENGINE SPEED AND NOISE LEVEL RELATED EXPERIMENTS

Six vehicles were tested to determine the effect of engine RPM for the noise levels, and the exhaust noise levels. The procedure described by AS 2240-1979 has been followed and the test microphones were set according to the procedures prescribed. Noise level meter (B&K 2215) was calibrated with a pistonphone (B&K 4230) at 94 dB(A). A foam windshield was used to obtain wind protection. The output of the noise level meter was fed into a noise level recorder (B&K 2306) with alphanumeric printing facility. A Sun Electric Inductive pick up Tachometer was used to measure the engine RPM. The engine has been considered as a point source for the stationary noise tests.

The exhaust noise levels of the test vehicles were first taken with their engine running at 1000 RPM. Then the engine speed was increased in 500 RPM increments and the noise levels were measured at each of these increased speed levels until a speed was reached that was just below or equal to the maximum power of the engine. This speed range was from 4000 - 6000 RPM. To average out the effect of changes in exhaust noise levels with the changing engine exhaust system temperature, the engine speed was returned to 100 RPM range and then the process was repeated. Four sets of readings were taken, and the average noise levels for each engine speed levels were measured and the values were plotted as per Figure 4.10.

Regression lines have been fitted to the raw exhaust noise levels versus engine speed data for each vehicle tested. The form of the regression equation was:

$$SPL = C + s R \qquad (4.17)$$

Where

SPL = exhaust noise level

C = Intercept - dB(A)

s = slope

R = engine speed -RPM

The results are given below in Table 4.8 below. Accordingly, it can be seen that the slopes of the regression lines do range from 0.00459 dB(A)/RPM to 0.00708 dB(A)/RPM, and hence the significance of increasing engine RPM to increasing noise levels is emphasized.

Table 4.8 Results of regression analysis for variation of noise level with engine speed

Type of Vehicle	Model of Vehicle	Regression Line	Correlation Coefficient
Passenger Car	Mitsubishi Magna	0.00459	0.98
Light Truck	Toyota Dyna	0.00511	0.99
HGV(MT) Medium Truck	Hino Transporter	0.00581	0.98
HGV (R) H/Truck	Layland Boxer	0.00663	0.99
HGV (B) Bus	Mercedes Benz	0.00513	0.99
HGV(T)Trailer	Mack	0.00668	0.98
HGV (MC) - Motor Cycle	Kawasaki 500	0.00708	0.99

Figure 4.10 shows variation of noise levels with different engine speeds

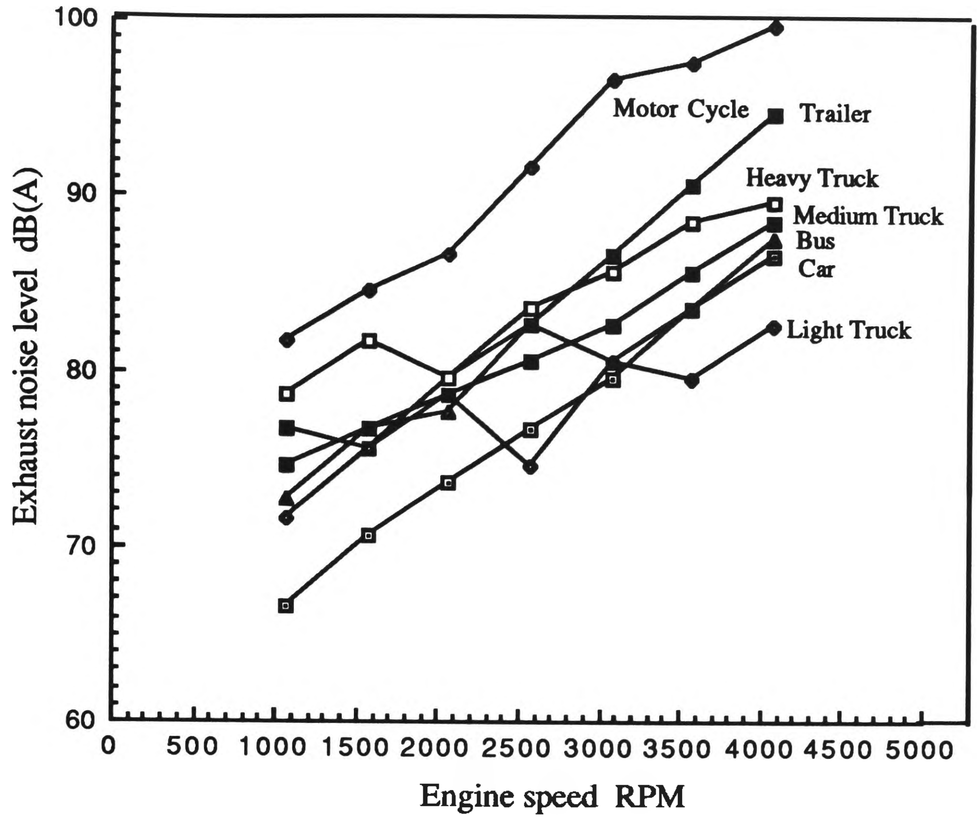


Figure 4.10 Measured variation in Noise levels with engine speeds

The correlation coefficients range from 0.96 to 0.99, and the average slope of the curve for all the vehicles tested is 0.00567 dB(A)/RPM. From the individual regression equations, and the average curve slope for all the vehicles, it was possible to calculate the change in exhaust noise levels according to the change in engine speed.

From the graph it can be noticed that smooth cruising speeds without any significant acceleration will help to reduce exhaust noise levels if the drivers pay attention to the manner of accelerating the vehicle, avoiding any unnecessary acceleration.

4.15 PREVIOUS TYRE NOISE SURVEYS

Tyre - road noise has been recognised as a very important source of vehicle noise. There seems to be no legal limit on noise from tyres, but there is much public sensitivity to the issue. Several mechanisms related to this issue had been discussed by Hayden (1971) who had suggested that the air pumping mechanism or monopole radiation is the most important mechanism of noise production for tyres. The other two tyre noise producing mechanisms are casing vibration and aerodynamic sources (unsteady airflows) (Hayden, 1971). Richards (1973) showed that tread vibration caused by the steady centripetal acceleration being modulated by tyre tread pattern or road surface can account for radiated noise.

4.16 FIELD EXPERIMENTATION DONE TO DETERMINE THE INFLUENCE OF TYRE AND ROAD SURFACE TO TRAFFIC NOISE

In order to obtain the required data to evaluate the tyre - road noise generation, a series of tests were carried out with a test vehicle. A Toyota Hilux (RN 85R) model Double Cabin type single chassis light utility pick-up having four wheels was used for the test. It was done on three different test strips: two (Motorway sprayed seal; Dense graded bituminous concrete) at the centre section of the Keira Street adjoining to the corner of the Campbell Street, and one at an open graded friction course surface strip, at 18th kilometre along the F 6 Freeway from Wollongong towards the Bulli Pass in Wollongong. Test period was on four consecutive Saturday mornings in the month of December 1991. A velocity of 65 km/h was selected as the acceptable speed, and a test speed was selected as 80 km/h. The "A" weighted peak noise level was received at fast response of a noise level meter via a FM microphone, and a FM radio receiver kept inside a car parked at the roadside. The test vehicle was fitted with four different sets of tyres with different tread patterns, one set at a time for each test separately.

One test was concentrated to measure the influence of vehicle speed for the tyre noise. Two types of tyre sets; Rib Type and the Block Type were used on two series of separate test runs with the same test vehicle and the tyre related noise measurements were recorded using the above mentioned test procedure. After the analysis of data obtained, they have been applied to linear regression analysis in order to determine the influence of the vehicle speed to the tyre noise.

4.16.1 Instrumentation and Measurement Technique for Tyre Noise Surveys

A frequency modulated (FM) type wireless microphone (Aristra - ECM 450) has been used to transmit the tyre noise through a radio frequency band range of 50 Hz to 15 kHz, and the radio signals have been received by using a FM radio receiver (Sony - ICF 40). The microphone was mounted at the underside of the rear wheel arch facing the trailing edge (0.5 meters away) of the rear left side tyre (Reference pp 209 of Appendix 3). The FM radio receiver has been kept on the rear seat of a car parked at the near side of the road, and the received radio signal related to the noise level was then fed into a precision noise level meter B&K type 2215, which was coupled to a Stereo FM tape recorder (B & K 7003) in turn (Reference pp 209 of Appendix 3). The tape recorder, microphone, receiver and the noise level meter have been checked for the charge level of their batteries. A pistonphone (B&K 4230) was used to calibrate the noise level meter at 94 dB(A). Ten minute noise samples were recorded for each sample tyre set. Some wet measurements were also taken on a rainy day. The recorded noise samples were analysed using a third octave noise level analyser (B&K 1613). Toyota Hilux Doble cabin (RN 85) (1000 kg) type utility pick-up was used as the experimental vehicle (Reference pp 210 of Appendix 3).

Table 4.9 shows the data obtained from the test tyres used in the experiments.

Table 4.9 Test tyre data

Type of Tyre	Make	Size and Ply Rating	Condition of Tyres
A- Highway	Olympic Trojan 130	1.85-14 / 8 ply (C)	Almost new
B- Block	Olympic P215SR 14	1.85-14/ 8 ply (R)	Almost new
C- Highway Retread	Beaurepairs Km Cap	1.85-14/ 8 ply (C)	Rebuilt
D- Highway worn-ou	Dunlop SP LT 5	1.85-14/ 8 ply (C)	Worn-out

Legend: R - Radial Ply; C - Cross Ply

The tyres were inflated to a pressure of 26 PSI (front) and 35 PSI (rear), and the unladen weight of the truck was 1000 kg. Some measurements also were made with a load of 2000 kg (20 bags of cement 50 kg each) in order to investigate the relationship of the weight on loaded axles to the tyre noise level. Table 4.10 shows the laden and unladen loads on the wheels of the test vehicle according to manufacturers specifications and the way it was loaded.

Table 4.10 Laden and unladen mass

	Offside Front	Nearside Front	Offside Rear	Nearside Rear
Unladen (kg)	150	150	350	350
Laden (kg)	350	350	650	650

4.16.2 Types of Tyres and Road Surfaces Used

Three types of road surfaces were tested for tyre-road surface interface measurements. They were: dense graded asphaltic concrete; sprayed seal, and open graded friction course. Figure 4.11 (a), (b), and (c) shows them consecutively.

Figure 4.12 (a), (b), (c), (d) show the types of tyres fitted to the test vehicle on separate occasions. They were Highway rib type (type A); random block type (type B); retreaded highway rib type (type C); worn-out highway type (type D).

Figure 4.11 (a) Dense graded asphaltic concrete

Figure 4.11 (b) Sparayed seal

Figure 4.11 (c) Open graded friction course

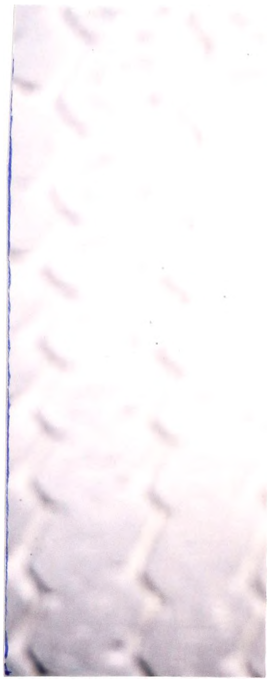


Figure 4.12 (a) Type A - Highway (b) Type B - Random Block Type

Figure 4.12 (c) Type C - Highway Retread

Figure 4.12 (d) Type "D" - Highway Worn-out

4.17 RESULTS AND ANALYSIS OF THE EXPERIMENT FOR SPEED NOISE RELATIONSHIP (GENERAL)

For A and B types of tyres tested it can be seen that the sound levels varied linearly with the speed. a linear regression analysis was made for this. Figure 4.13 (a) and (b) show the linear regression results obtained for "A" and "B" types of tyres from the measurements obtained.

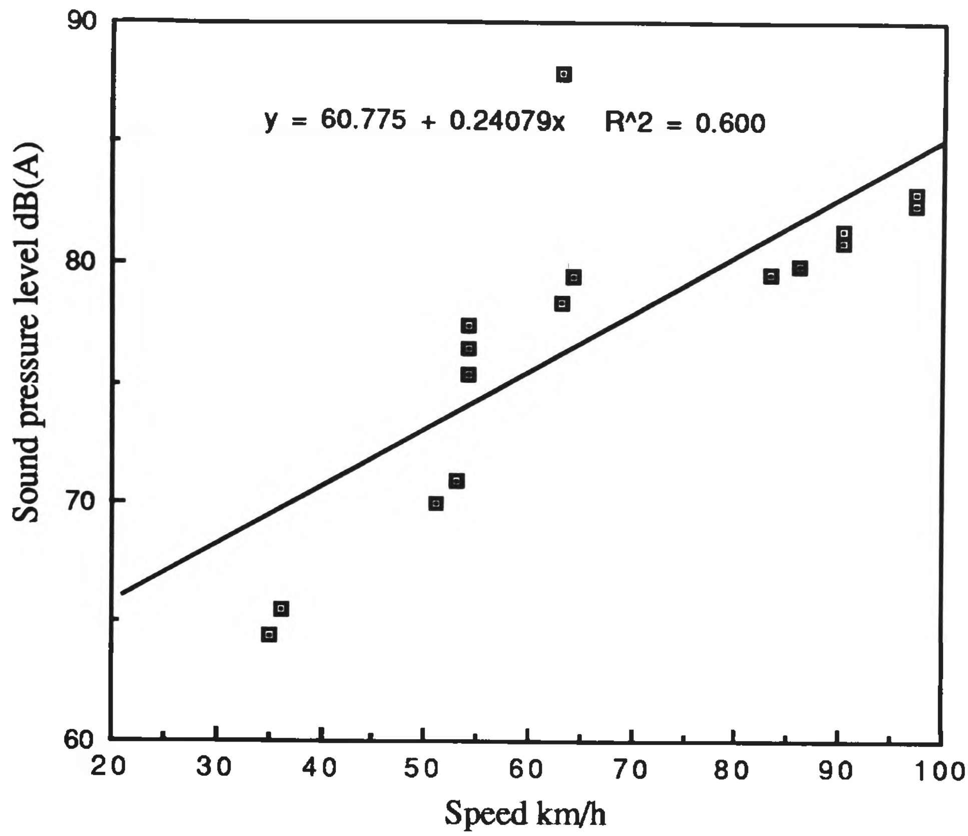


Figure 4.13 (a) Results of linear regression analysis for tyre type "A"

Table 4.11 shows the regression parameters, and the regression lines found.

Table 4.11 Regression parameter and regression lines

Type of Tyre	Coefficient of Correlation	$dB(A) = a \log_{10} V + b$		Standard Error of Noise Level dB(A)
		a	b	
A	0.998	36.4	9.7	0.58
B	0.996	37.3	8.7	0.66

Legend: a and b are regression coefficients.

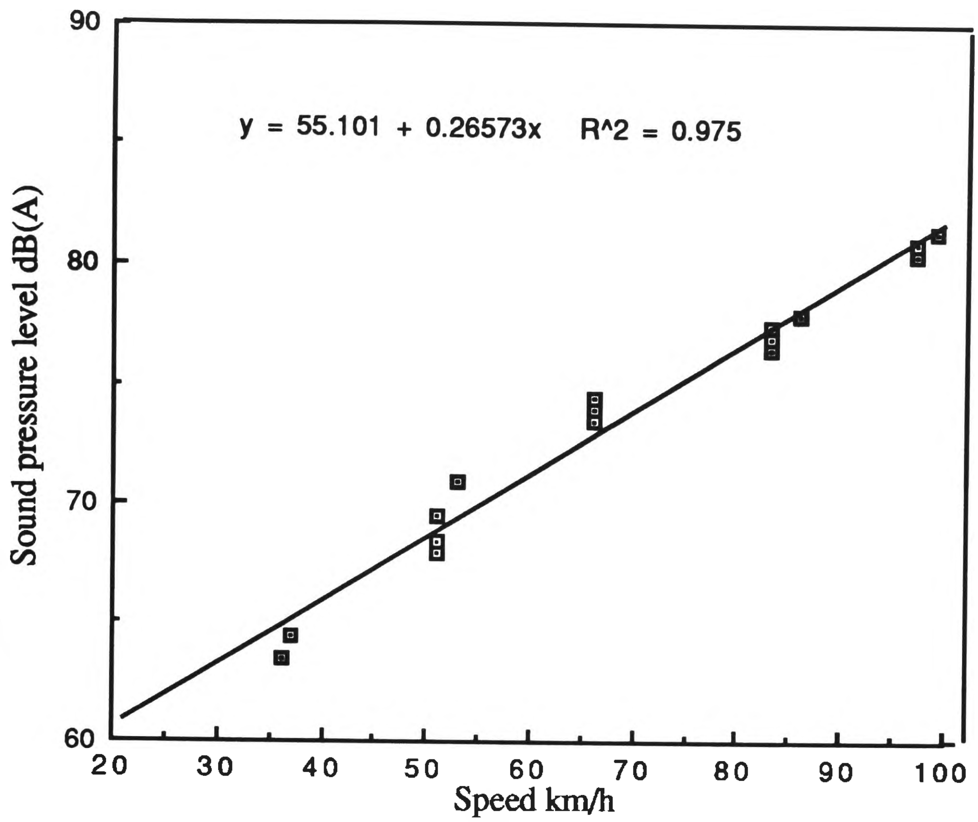


Figure 4.13 (b) Results of the regression analysis for tyre type "B"

Analysis of noise levels over a third octave band range is given in Figure 4.14. This shows the result for block type tyre (Type B) for 10 consecutive runs of analysis on open graded friction surface at 80 km/h. The close agreement between the measured standard deviation and the instrument deviation of the noise level shows that over the range of frequencies of 100 Hz to 10 kHz, the sampling statistics are a major source of the variance for the frequency spectra over this range. A small discrepancy exists due to the low sound levels received beyond the prominent tyre noise and have been neglected.

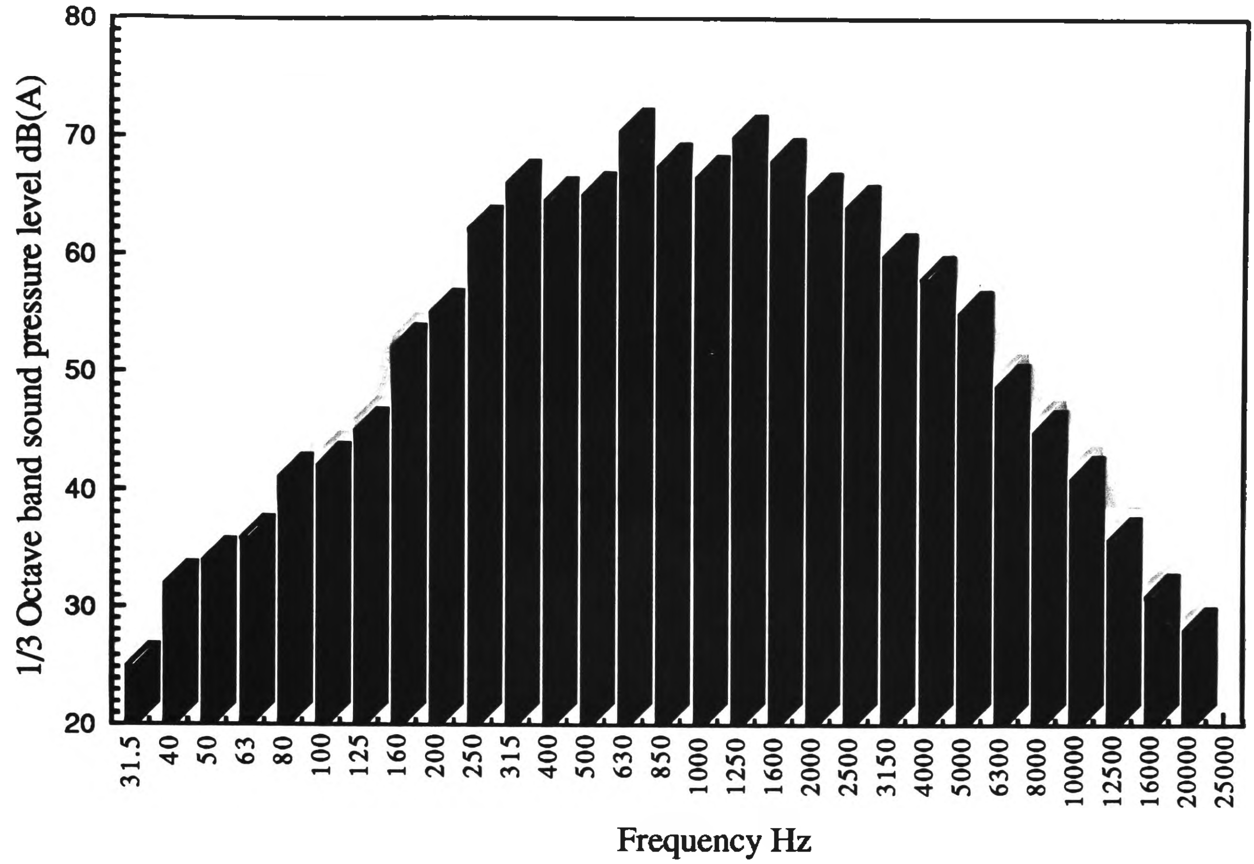


Figure 4.14 Analysis of the tyre noise spectrum

4.18 RESULTS AND ANALYSIS OF EXPERIMENT FOR VARIOUS TYRE TREADS, ROAD TEXTURE AND LOAD

The test parameters investigated were tread pattern, speed, road surface texture, and the load. The effects of each of these parameters were tested separately and the regression parameters obtained using linear regression analysis appeared to the measured values of sound level in dB(A) and to each of the parameter separately.Table 4.12 shows the regression parameters for measured sound levels and the speed of the test vehicle. For type “A” (Highway Tyre) the mean of the slopes obtained was 33.65 and standard deviation was 5.5 on a dry roadsurface.

Table 4.12 (a) Regression parameters for type “A” tyre on different road surfaces

Type of Surface	Slope (m)	Intercept (C)	Coef.of Correlation
Dense Graded Asphaltic Concrete	33.2	8.9	0.975
Sprayed Seal	34.1	11.8	0.982

and,

Regression equation $S = m \log_{10} V + C$ (4.18)

Where

S = surface variable

m = slope

V = speed

C = intercept

Table 4.12 (b) Regression parameters for tyre type "B" on different road surfaces

Type of Surface	Slope (m)	Intercept (C)	Coefficient of Correlation
Dense Graded Asphaltic Concrete	42.0	3.6	998
Sprayed Seal	40.1	3.4	998

Table 4.12 (c) Regression parameters for tyre type "C" on different road surfaces

Type of Surface	Slope (m)	Intercept (C)	Coefficient of Correlation
Dense Graded Asphaltic Concrete	32.0	8.9	0.992
Sprayed Seal	27.8	18.9	0.995

Table 4.12 (d) Regression parameters for tyre type "D" on different road surfaces

Type of Surface	Slope (m)	Intercept (C)	Coefficient of Correlation
Dense Graded Asphaltic Concrete	19.6	32.5	0.997
Sprayed Seal	28.8	17.0	0.985

4.19 FINDINGS RELATED TO EFFECT OF TYRE TREAD PATTERN TO NOISE LEVELS

Figure 4.15 shows the noise levels measured by using separate sets of different types of tyres on dense graded asphaltic concrete surface. At speeds below 50 km/h the noise levels apear not to be significant. It was very clear that the noise levels of the block type traction tyres (Type B) have proved their worth in cutting the noise levels at high speeds. The blocks of these radial tyres were long enough and at sufficient angle to feed into the contact patch without heel and toe wear. Their treads were stronger and deeper. The steel belts used stiffened the tread significantly, reducing the deflection and making a firmer foundation for the tread. On wet surfaces the type "A" and "C" were as quiet as type "B". Type " C" showed a higher noise levels due to the heavy carcass resulting from the rebuilding process. Type "D" showed about a 5 dB(A) reduction due to the non availability of any tread layer accompanying its smoothness, but it is dangerous to use this type of tyre due to very low skid resistance they have on wet surfaces.

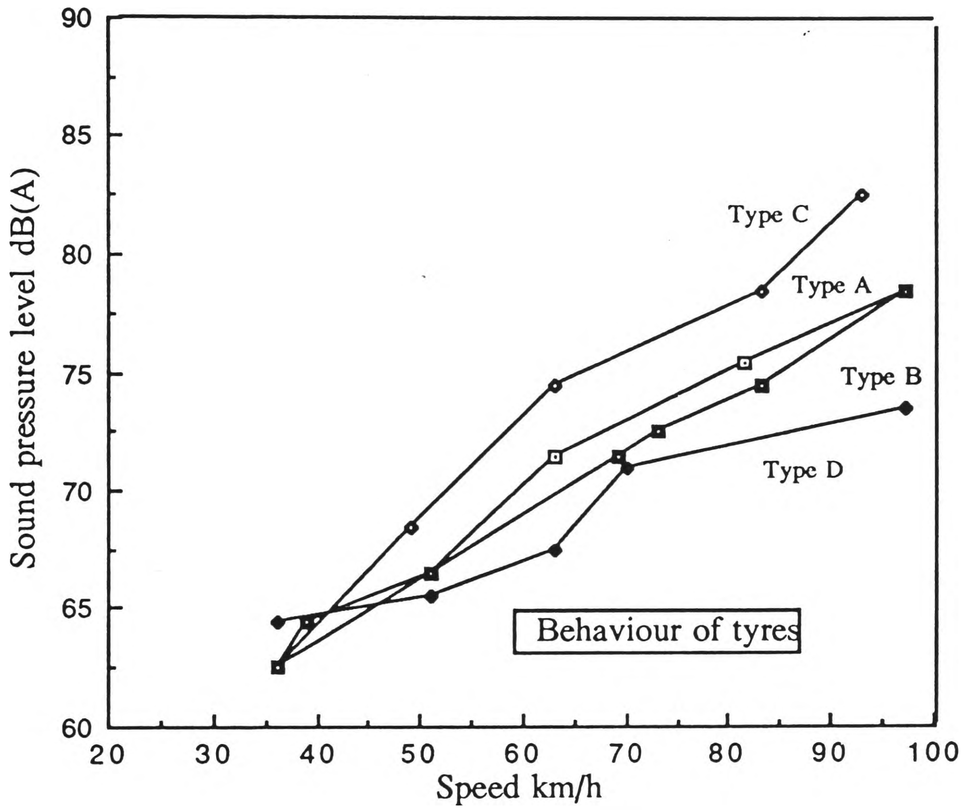


Figure 4.15 Behaviour of four different treaded tyres on dense graded surface

Smooth or bold tyres (worn-out treaded) lack traction and when the roads are wet, their skid resistance will become very poor and they are lacking the power to grip the road surface (skidding). Tread layers handle wet conditions different to that of bold tyres. Such tyres squeeze out the water layer on the road when the road is wet and allows a dry surface contact between the tread and the road surface. For these reasons, smooth tyres as a mean to cut down tyre noise seem futile. Figure 4.16 shows the effect of 4 different types of tyres and the levels of noise generated by them when come in contact with open graded friction course.

Accordingly, the types of tyres can be ranked as follows. Type "B" - block type tyre which has small composite blocks of random size diagonally across the width which scrambles the vibration resonances, and hence runs more quietly than tyre types "A" and "C".

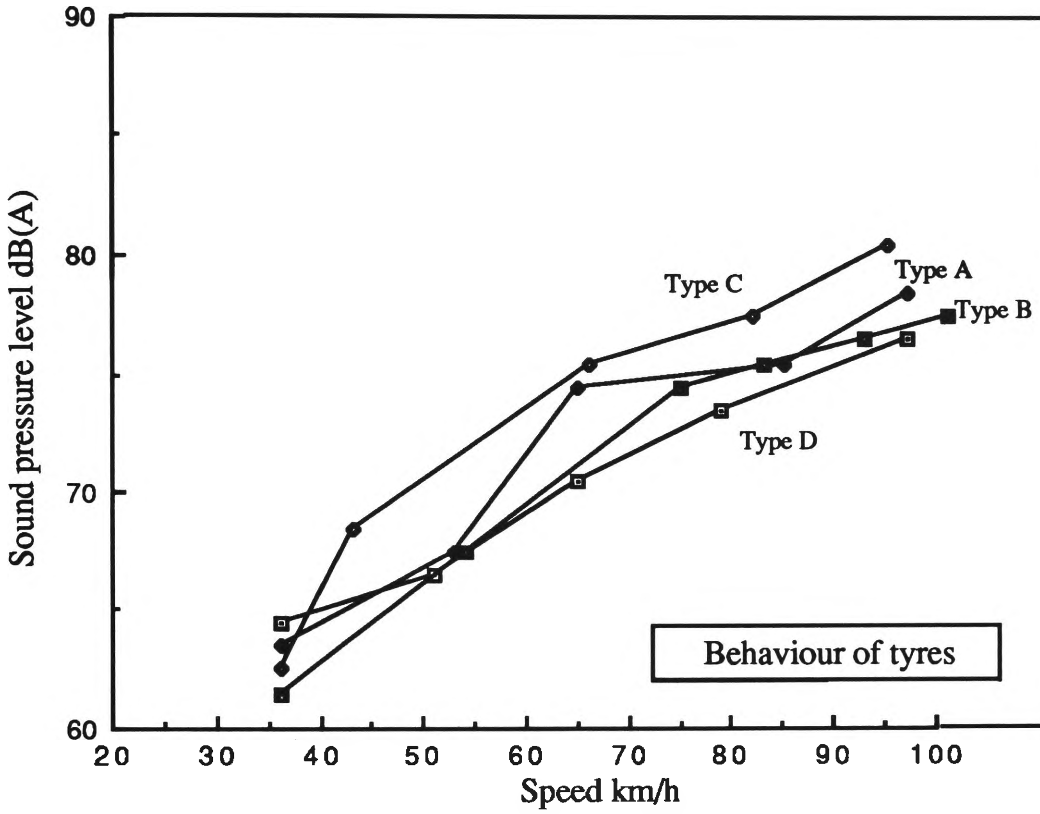


Figure 4.16 Behaviour of 4 different tyres on open graded friction course.

Figure 4.17 shows the effect of spray seal type road surface on noise levels as per the results of the field test done.

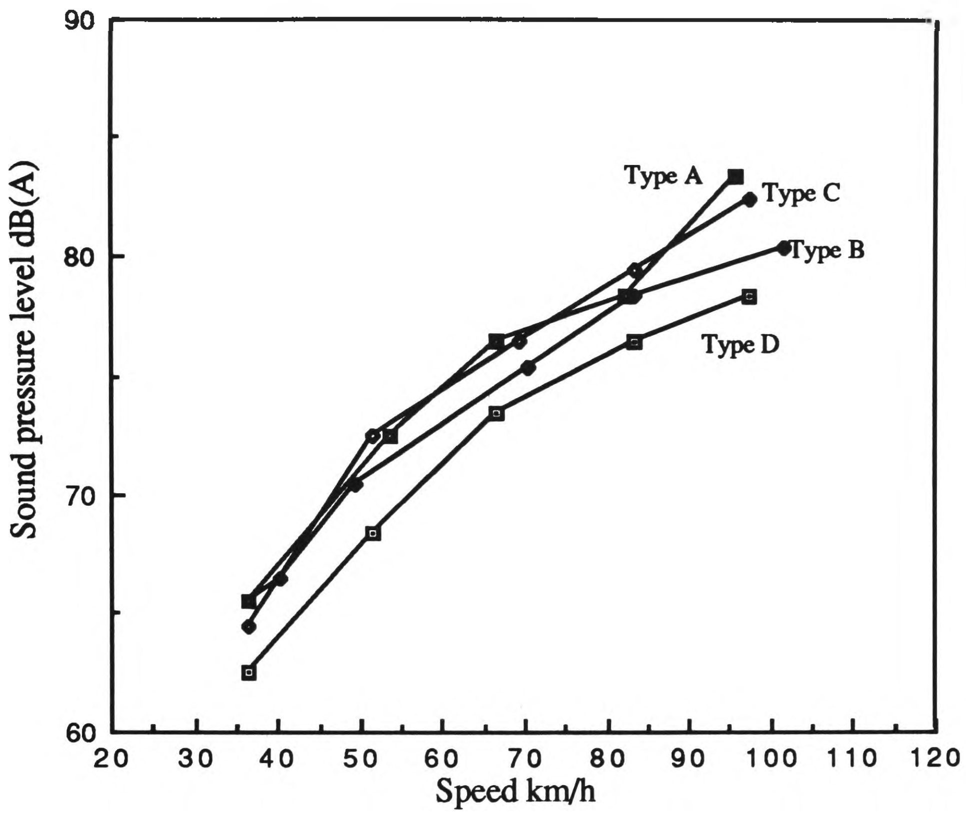


Figure 4.17 Behaviour of four different treaded tyres on spray seal surface

4.20 FINDINGS RELATED TO ROAD SURFACE TEXTURE

For the purpose of measuring the effect of the road surface texture on the road noise, a test was done using a set of worn-out tyres fitted to the test vehicle. A third type of road surface where an open graded test friction course was available along F 6 Freeway - Wollongong was also utilised for the experiment in addition to the test strips at Keira Street - Wollongong. Noise levels generated over three different road surfaces were plotted as shown in Figure 4.18.

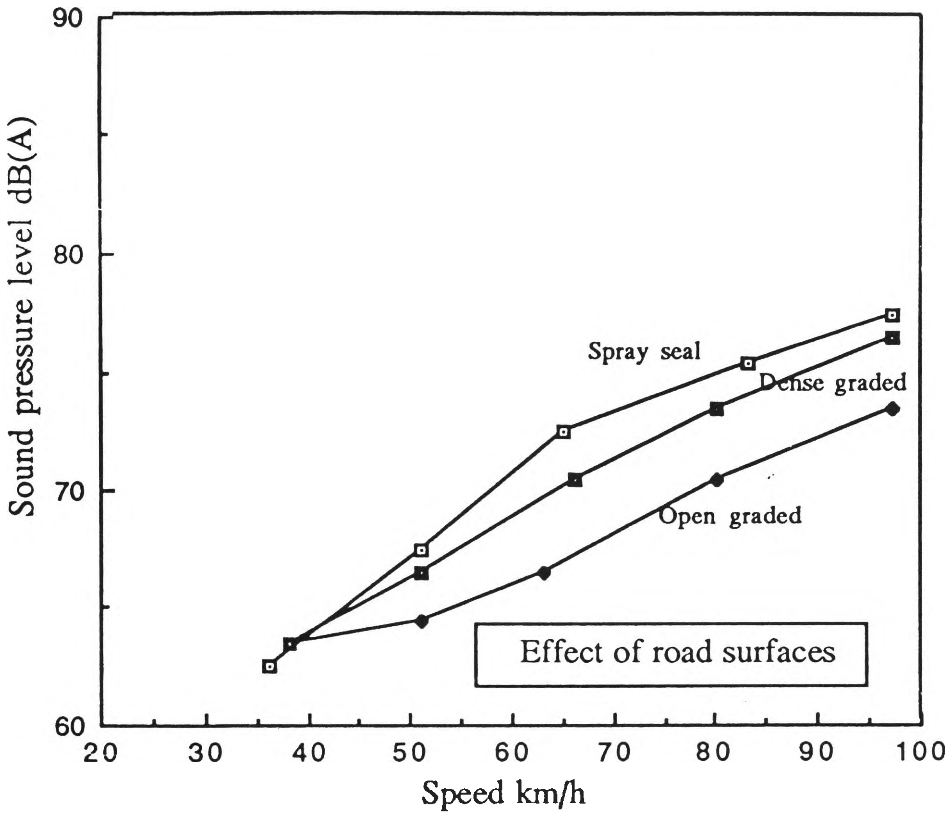


Figure 4.18 Noise levels generated by 3 different road surfaces

4.21 RESULTS AND ANALYSIS OF EXPERIMENT ON VEHICLE LOAD - TYRE NOISE RELATIONSHIP

A test was done using four different types of tyres on an open graded surface by increasing the load from unladen to laden by 2000 kg. Table 4.12 shows the load distribution on different axles on laden and unladen weights. Table 4.13 shows a test result.

Table 4.13 Test results of load related experiment

Surface	Noise Level Unladen dB(A)	Noise Level Laden dB(A)
Open Graded Friction course	78	81.5

Figure 4.19 shows the increase noise level due to application of heavy loads. It should be noted that the overloading of vehicles should be avoided in order to obtain better results from the traffic noise mitigation exercise.

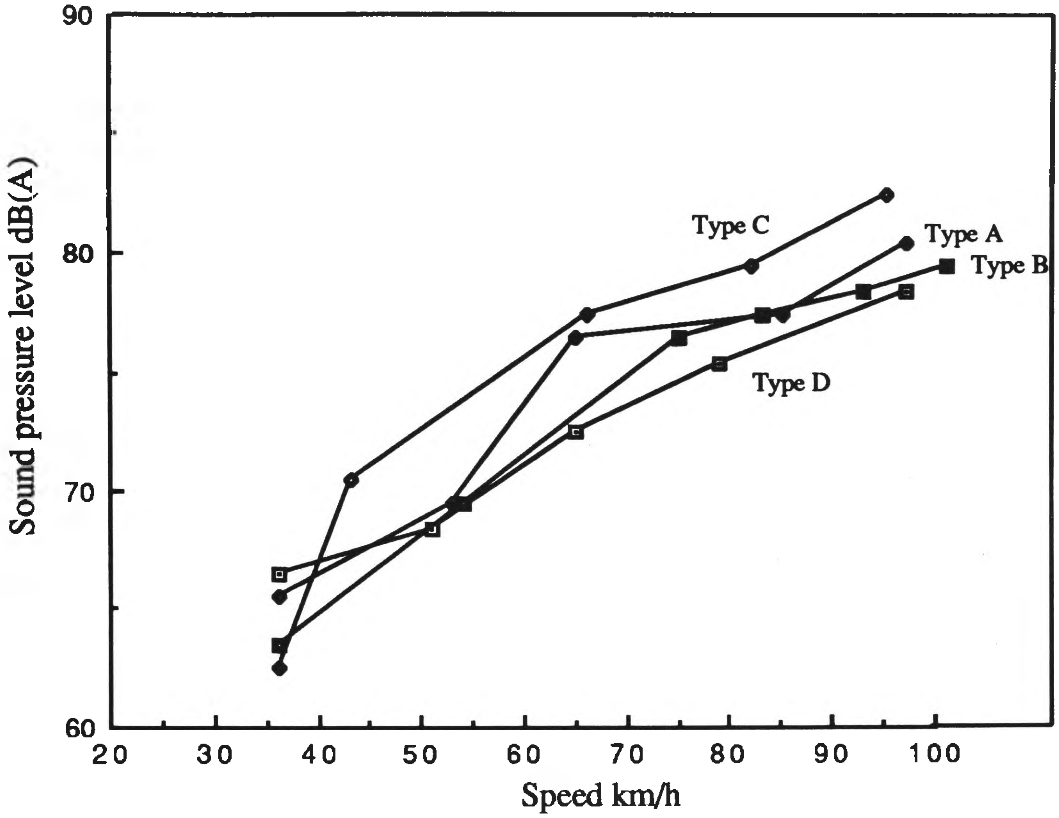


Figure 4.19 Increase of noise level due to increased load

4.22 ANALYSIS OF TYRE NOISE SPECTRUM

A weighted third octave band spectra was obtained by analysing the noise levels recorded for different types of tyres on different road surfaces as mentioned above. Frequency range between 1 to 2 kHz shows the maximum of the noise spectra. The rebuilt tyre shows a peak level at 250 Hz due to rotation harmonics of the heavy tread layer. The rib type tyre shows about 500 Hz increase compared with the block patterned tyre. Tyre noise spectrum analysis is shown in figure 4.14.

4.23 CONCLUSION

As noted in chapters two and three traffic noise reduction at source (vehicle) is an area which has attracted the attention of a number of researchers. However their findings show a number of discrepancies. It has been the objective of this research to show that there is a meaningful relationship between the types of tyres, road surface and the rolling noise levels generated. In addition this research shows that the traction type block tyres which have small composite blocks of random size diagonally pan across the width of the tyre do avoid the vibration resonances by scrambling them, they are more effective in noise reduction than the highway type rib tyres. The load - noise relationships also have to be considered as shown in this research, whereas some of the authors have noted that there is no significant relationship between these two factors. It is expensive to resurface with the open graded friction courses. But it is required to encourage the authorities concerned to be at least aware of the requirement of resurfacing the arterial road stretches in critical areas with friction course of open graded asphalt. It is possible to use the scrapped road construction material from the reconstruction sites as the base layers of the new construction after recycling, in order to minimise the capital costs incurred in layingthis type of surface.

It was found in this study that, the noisiest surface was the sprayed seal surface and the quietest surface was the open graded friction course surface. At speeds above 50 km/h the open graded course showed a high difference of about 5 dB(A). The dense graded bituminous concrete surface has shown about 3 dB(A) lower noise level than the sprayed seal surface.

A traffic noise prediction model to match with Australian Traffic environment in Illawarra Region of New South Wales was developed as a result of this thesis. It can be used for prediction of traffic noise and it can be modified to suit with the traffic conditions in any state of Australia after further research.

More strict vehicle speed limits, and allowable vehicle noise levels should be enforced in traffic noise affected areas, and rerouting of the heavy vehicles should be taken into consideration where there is a high percentage of heavy vehicles are flowing through the residential areas to mitigate the impacts of traffic noise. More stern action should have to be taken against those who violate the speed and noise limits.

CHAPTER 5

GENERAL CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

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5.1 INTRODUCTION

All of us do contribute to the traffic noise problem, some of us more than others. To mitigate the adverse effects of this worsening traffic noise problem, it is essential that we the general public take more interest in traffic noise mitigation exercise.

If the individual attention can be attracted towards this problem, the objectives of the traffic noise mitigation can be achieved in more environmentally friendly, efficient and economical way reducing the harmful effects caused by the traffic noise. All drivers should be more alert regarding the noise levels emitted from the vehicles driven by them.

Reducing the vehicle noise levels at source, and erecting an obstacle between the source (vehicle) and the receiver (residents) have been seen as effective methods to mitigate traffic noise, in addition to the other noise mitigation strategies such as road construction technology and local area traffic management. An integrated approach to employ the optimum combination of all the four traffic noise mitigation strategies will enable an optimum solution to the problem.

5.2 RESEARCH APPROACH

A comprehensive study related to vehicle noise mitigation using the available motor vehicle technology giving special emphasis to the tyre noise area, and using the available noise barrier technology was carried out in order to highlight the problem areas and review the noise abatement techniques. The characteristics of the types of noise barriers available in Wollongong area of Illawarra region of the State of New South Wales have been examined with respect to their location, construction, material, condition, aesthetic appearance and the efficiency in noise mitigation. The data related to above factors of the existing barrier types in the region and the types of instrumentation utilised have been tested, observed and discussed.

In order to understand the role of the vehicle noise reduction at source, data related to tyre noise, tyre road interface, noise levels related to engine speed (RPM), vehicle speed and acceleration, different flow levels, different heavy vehicle pecentages, different types of vehicles also have been investigated and been discussed.

By integration of the data gathered related to the vehicle noise levels at source, and traffic noise levels at with barrier and no barrier situations for different types of traffic noise barriers, proposals have been done for future use. Interest of the concerned authorities has been drawn to use more effective type road surface material at noise affected areas, in addition to erection of effective types of noise barriers.

5.3 GENERAL CONCLUSIONS

Traffic noise environment in Australia is such that a high percentage of heavy vehicles are flowing on its urban and rural roads network. Being an industrial and agricultural based country which is producing products for own use as well as for export market, it is a must that the heavy vehicle should be authorised to run on all over its road network for collection and distribution of these products and distribution of commodities. Hence, it is a very difficult task to enforce more restrictions on heavy vehicles. But it is possible to find the means of reducing the impacts caused by the higher noise levels produced by them.

The economic aspects of various techniques for suppressing the impacts of traffic noise were considered under two categories; (a) reducing the noise at source by way of quietening the vehicles; and (b) reducing the noise transmitted beyond the right - of - way by appropriate noise barrier technology and proper building materials.

Quietening of vehicles would probably provide a great noise reduction potential. The diversion or re-routing of heavy trucks to alternate routes-more remote from the existing community might be cost effective strategy for existing situations under very limited circumstances. Among arterial road measures, the building of road side barriers would be very economical. Furthermore, barriers can provide as much noise reduction potential as any other highway construction measure.

It is possible to reduce the traffic noise impacts on neighbouring communities of the arterial roads, by actions taken beyond the right-of-way. Specific land use strategies including, restricting of the use of land bordering the right - of- way to: (a) clear buffer zone; (b) structures that are normally occupied, such as ware houses and storage facilities; (c) Structures and housing facilities that normally involve high self generated noise levels such as shopping centres and manufacturing complexes; and (d) Properly sound treated high rise structures, that might provide some additional noise reduction to the remainder of the community through shielding can be applied. Eventhough the application of such land use strategies to existing communities, probably would not be economically practical in most cases due to high costs associated with the acquisition of land in developed urban community, all the techniques have some merit for application to future communities where the required zoning regulations could be imposed before an effective landuse is developed.

The most cost effective measures are those related to land use strategies: for example, zoning the land bordering the right-of-way for structures those house activities least sensitive to intruding noise such as storage facilities etc. Appropriate sound treatment of community structures can yield substantial interior noise reduction, but the cost per dB(A) is relatively high.

The role of the vehicle regulatory authorities is also very important in traffic noise mitigation exercise. It has been observed by the author of this thesis that most of the drivers are accelerating their vehicles unnecessarily causing very high individual vehicle noise levels. The worst contributor to the excessive unnecessary acceleration was the motor cycle which has been grouped under the category of HGV (MC) by the author due to extremely higher noise levels generated by them. Immediate action has to be taken utilising the media such as newspapers, radio and the television, to alert all the drivers to mind their acceleration levels. More stringent speed limit regulations have to be applied within the problem affected residential area road network, for the vehicles grouped under heavy vehicle classification (specifically below 60 km/h), and for the vehicles grouped under car classification (80 km/h).

According to personal observations of the author, most of the mid aged passenger cars have been fitted with the modified sports silencers by the owner drivers for their own driving pleasure, to hear heavy silencer beats whilst driving neglecting the harm to the general public caused by those sports type silencers. Some of the vehicles observed were seen running with faulty silencers due the negligence of the drivers. They are not only causing the higher intolerable noise levels, but cause the air pollution also due to their higher backpressure levels. Penalties for using modified and faulty silencers should be increased, in order to get rid of the worst rate of noise exceeding levels by them.

If the drivers of individual vehicles pay a little more attention regarding the maintenance of their vehicle, and their driving behaviour, the noise levels cause by the individual vehicle can be effectively reduced. When the unnecessary levels of acceleration is avoided, the engine RPM will be maintained at a reasonable level, and hence the excess noise levels generated will be reduced, and the fuel economy of the vehicle also will be improved. Moderate acceleration will enable us to avoid unnecessary braking as well, and thus enable us to mitigate the excessive noise levels generated due to extraneous braking applications. In addition, the moderate speed levels such as 60 km/h will have to be observed on the roads of residential areas. Legal speed limits have to be adhered. If we will start to use the random block type radial tyres.

Most of the truck noise levels measured have been noted as excessive caused due to higher speeds, acceleration and braking. When the air brakes of the heavy vehicles were applied at high speed runs, excessive noise levels are generated due to higher braking force coefficients. The worst noise levels have been noted from the empty trucks running at excessive speeds. This is due to bounce and rebound conditions of the empty body due to action of the suspensions. Trucks with leaf spring type suspension and the quick release levers have shown higher noise levels than their counterparts such as pneumatic suspensions and permanently locked couplings. It is understood that the retraining exercise specially for the the truck drivers have to be conducted in order to emphasise them the acceleration and operational and maintenance aspects of the heavy vehicles. The HGVs running at excessive speeds do not only cause higher noise levels but they damage the roads surface as well, thereby creating pot holes and bumps on the road surface, which in turn will generate higher noise levels when thousands of vehicles run on those surfaces in future. The proposed road user charges for the heavy vehicles have to concentrate on the excessive noise levels generated by those high speeding truckers and to make them pay for the damages caused by them.

Building the houses facing away from the line of sight of road, having the doors and windows opened away from the direction of road also helps to reduce the impact of the traffic noise to the residents. The wall facing the road will act as a solid noise barrier according to this construction.

Earth mounds have been seen as the most effective type of noise barriers in Wollongong region. These mounds have to be made during construction stages. They are visually acceptable and attractive, and they do give effective and permanent acoustic performance. Economy of constructing the earth mounds as noise barriers depends on the cost of the right - of - way. It has been noticed that the earth mound type noise barriers can be economically constructed where excess cut soil is freely available. Some of the earth mound type barriers have a slope of 1:3 in order to avoid erosion, but some of them like the ones made with poor quality soils such as silty clay require a higher slope such as 1:5. Grass growing over the earth mounds increase the visual effect of the earth mound type noise barriers, in addition the grass also gives a certain attenuation due to ground cover. These type of barriers do require no maintenance other than planting the grass to avoid the erosion due to rain. Earth mound type barriers do enhance the aesthetic effect of the land in addition to its noise mitigation effect. This type of barrier is the most suitable type for noise attenuation for sites such as playgrounds.

Noise attenuation of asbestos cement type barriers is comparatively higher than the timber type barriers. They do give a reasonable noise attenuation comparative to the timber type noise barriers. Zincalume Steel type noise barriers have shown their effectiveness a good type of domestic type noise barrier. They have proved the acoustical efficiency and aesthetical attraction as well, Eventhough they are a little expensive than the timber, clay brick and asbestos type barriers.

Clay brick type barriers have shown their effectiveness due to their higher mass and the thickness. But due to a higher percentage of exposed open area will reduce the effectiveness of them. Their maximum efficiency can be obtained by putting them up right around housing premises avoiding the short circuiting of the noise path and reducing the open area. A combination of earth mounds and either timber or clay brick or steel or asbestos type barrier will provide more attenuation due to height, and the multiple characteristics of the combination.

Thick varieties of tree plantations do give an aesthetic attraction to the guarded properties. But, in order to achieve a reasonable level of attenuation, the thickness of the bush have to be at least 30 meters.

Benefits of the random block type radial tyres also has been tested and proved to be most effective among the types of the tyres which have been subjected to the noise test under this thesis project. It is true that the highway type tyres are more economical than the random block type tyres. But as far as the vehicle noise mitigation at source is concerned, the use of random block type radial tyres have been emphasized.

Benefits of the use of duel mufflers for the heavy goods vehicles also were studied with the observations done. By reducing the engine backpressure level, the duel muffler systems have shown their effectiveness over the single stack type silencers for the heavy vehicles. It is necessary to encourage the owners of the in-service heavy vehicles to get their vehicles fitted with duel mufflers (Reference pp 206 of Appendix 3).

The effectiveness of the open graded friction course for the road surfaces have also been emphasised as per the test results done on the Bulli heights of the F-6 Freeway. The attention of the authorities concerned have to be drawn to apply the open graded friction course to the road surfaces of the noise affected residential areas. The old discarded dense graded road materials removed from the road stretches where the new open graded layers are applied, can be recycled to be used as a base course for the new constructions.

Traffic noise prediction models which have been developed so-far by different researchers in different countries may be suitable to the traffic environments of their countries, but most of them do not interpret the Australian traffic environment, and they have many discrepancies in application here. Hence, it is a must that required measurements will have to be taken by the authorities concerned to develop more appropriate traffic noise prediction model to suit with the Australian national requirements.

5.4 RECOMMENDATIONS FOR FUTURE WORK

More fruitful work related to vehicle noise reduction at source can be done by developing the motor vehicle technology. Encapsulation of engine, transmission, differential, application of noise absorbent material to provide the effects of barrier, absorption and damping to cover the noise generating units, lowering the wheel arches, providing automatic chassis lubrication (for the heavy vehicles), by generating a damping wave spectrum by using an electronic device inside the mufflers, more interesting research can be done if funding and the required resources are available in the future for the traffic noise mitigation research project.

The author of this research has designed a test rig for testing the different tyres of different test patterns together with their interface to different road surfaces at the same time. This test rig can be fitted inside an anechoic chamber of 3 X4 meters. An electric motor operated with AC current is used to drive a spring loaded hollowed concrete roller mounted on a centre axle supported with ball bearings to reduce the axle noise. Another shaft is belt driven by the same motor on to which the test tyre can be fitted. When adjusted the tyre will rotate on the concrete roller on which applied specific type of a road surface material. Test tyres can be made with worn-out tyres by cutting specific tread patterns on them using an electric soldering iron by attaching a specifically made Steel cutting edge to its soldering head. Same rig can be used to cut the specific tyre patterns by rotating a tyre on the fitted axle by setting the heavy duty soldering iron to touch the carcass of the tyre whilst the tyre is being rotated. Through a hole made in the rotating hollowed concrete drum roller, a FM type wireless microphone can be inserted for the purpose of receiving the pumping noise of the tyre. The signals generated by the FM wireless microphone can be received via a FM radio receiver which can be connected to a FM tape recorder directly to record the pumping noise of different tread patterns and the road surface noise without the influence of the background noise.

This test rig can be manufactured according to the specifications of the author at a very low cost if funding is available to purchase the required materials. Author is willing to devote his time and his automotive and transportation engineering expertise to develop this test rig for the benefit of engineers and the scientists who are engaged in traffic noise reduction research by developing tyre and road surface technologies.

It can be predicted that the above test rig may solve all the weaknesses of the Hayden (1971) method to test the tyre road interface in tyre noise generation, and may contribute to the advancement of the Transportation Engineering in the future.

The author of this thesis has already collected required data and planned to develop more effective types of mufflers for all the types of vehicles, by utilising his automotive engineering expertise, together with the latest computer software technology. This will be achieved by developing a further modification to the Volume 5 of the Finite Element Analysis software package for fluid flow analysis. When developed, it can be more beneficially adapted to model different specifications of the motor vehicle mufflers to suit with more restricted engine noise emission levels.

The author also wishes to conduct further drive-by noise surveys in different states in Australia to develop a more advanced traffic noise prediction model which may be adaptable to Australian national traffic environment.

Further development to noise barrier technology is also planned by the author for testing of panels made of different types of building and barrier materials in a specially designed anechoic chamber, replaying pre-recorded traffic noise signals via speakers and receiving the transmitted noise levels through the panels by using a different set of microphones.

Some units of a truck which are very important as vehicle noise mitigation devices, which needs further attention and research for modifications and encapsulation are shown in pp 203-205 in Appendix 3.

REFERENCES

ADR 39 (1985) "Maximum Permissible Noise Levels for various Classes of Motor Vehicles Together with the Test Procedure" *Australian Design Rule* - Federal Ministry of Transport

Anderson, G.S., Miller, L.N and Shadley, J.R (1973) "Fundamentals and Abatement of Highway Traffic Noise" Federal Highway Administration, National Technical Information Service - USA, Report PB-222-703

Anon. (1989) "Lighter Action Z.F. Gear Boxes for P.S.V.S. Vehicles" *A Journal Article of Transport Engineer,* Jrl of the Institute of Road Transport Engineers (UK), August, p 26

Anon. (1990) "Trying to Cut Tyre Noise" A Journal Article of Transport Engineer, *Jrl of the Institute of Road Transport Engineers* (UK) August, pp 16-17

ADR 28 (a) (1976) "Objective Test Procedures and Criteria for Noise Emissions from Motor Vehicles" *Australian Standards* - Federal Ministry of Transport

AS 1055 (1978) "Noise Assessment in Residential Areas" *Australian Standards,* A Publication of Standards Institution of Australia

Bolt, Beranek and Newmann (1976) "Highway Noise Generation and Control" *A Report on National Cooperative Highway Research Programme (NCHRP)* , 173, Los Angeles, California, USA, pp 52-68

Brown, A.L. (1975) "The effects of a Freeway on Community Traffic Noise Levels" *Proc Conference on Metropolitan Transport - The Way Ahead ?* Institution of Engineers, Australia: Melbourne

Brown, A.L. (1980) "The Noise Response Relationship Near a Freeway" *Proc 9th ARRB Conference 9 (6)* , pp 248-62

Bruel and Kjaer (1988) "Acoustic Noise Measurements" *A Hand Book Dealing with the Basic Principles of Noise Measurements While Noise Control* , pp 1- 22

Bruel and Kjear (1978) "Measuring Sound" *A booklet Containing basic Questions and Answers to a New Comer of a Noise Measuring Programme*, pp 1-32

Bryant, J.F.M. (1975) "Traffic Noise and the Community" Australian Road Research Board - *Research Report - ARR 23*, Section 25.8

Burgess, M.A. (1977) "Noise Prediction for Urban Traffic Conditions related to Measurements in the Sydney Metropolitan Area" *Applied Acoustics*, 10, pp 1-7

Commonwealth of Australia (undated) "Vehicle Construction, Equipment and Performance Standards for Road Vehicles" *Draft Regulations of Department of Supply and Transport endorsed by ATAC*, Section 27.1-34.3

Delany, M.E. (1972) "Prediction of Road Traffic Noise" *Acoustical Report of National Physics Laboratory AC 56*, Proc International Noise Conference, Washington

Department of Environment (DoE), U.K. (1975) "Calculation of road Traffic Noise - (CORTN)" *Method for Measurement of Road Traffic Noise*, H.M.S.O.

Flangan, W. (1972) "Recent studies give unified picture of tyre noise". *SAE Journal of Automotive Engineering (USA) - (April 1972), pp 15- 19,* Compiled from reports submitted by the National Bureau of Standards (UK), General Motors, Rubber Manufacturers Association (UK), and Truck Tyre Noise Sub Committee (UK)

Gorden, C.G., Galloway, W.J., Kugler, B.A., and Nelson, D.L. (1971) "Highway Noise - A Design Guide for Highway Engineers" *Report No: 117 of the Highway Research Board* - USA.

Hasall, J.R and Zaveri, K (1988) "Acoustic Noise Measurements" *A hand book in Noise Measurements*, Bruel and Kjaer, pp 1-32

Hayden, R.E. (1971) "Roadside Noise from the Interaction of a Rolling Tyre with the Road Surface" *Proc Purdue Noise Control Conference*, Purdue University, Purdue, USA, July 14-16, pp 62-70

Health and Safety Executive (1990), " Noise at Work Regulations" *Information Leaflets for General Public Regarding Noise Regulations at Work*, 1, Cheapstove Place, London, W2 4TF

Hochrainer, R. (1990) "Searching for facts on Tyre Noise" Proc of the Conference Organised by A. V. L. List GmbH - Austria, Jnl Institute of Road Transport Engineers (UK), September pp 10-12

Hothershall, R. (1990) "Searching for facts on Tyre Noise" proc of the Conference Organised by A. V. L. List Gab H-Austrila, Jnl. Institute of Road Transport Engineer (UK), Septmber. pp 10-12

Hothershall, D.C and Salter, R.J. (1977) "Transport and the Environment" Crosby Lockwood Staples: London, p 230

International Standards Organization (ISO) (1975) "Acoustics - Method for Calculating Loudness Levels" *ISO paper No: 532*

Jameson, G.W. (1979) "An Interim Report on the suitability of Paling Fences as Noise Barriers. *CRB Report No: 082208*, pp 1-6

Joanne, E., Kleanhenz and Steven, D. S. (1981) "Fuel Efficient Exhaust Systems" SAE Paper No 81058, " Controlling Truck Noise" of Warrandale, P.A., *Collection of Professional Papers of the Soc of Automotive Engineers (SAE)*, USA, pp 101-108

Kennett, P. (1990) "Searching for Facts on Tyre Noise" *Jrl Inst of Road Transport Engineers* (UK), September, pp 16-17

Langdon, F.J. (1976) "Noise Nuisance Caused by Road Traffic in Residential Areas" Part (i), *Jrl Sound Vibration*, 47(2), pp 243-282

Lawrence, A., and Burgess, M.A. (1977) "Road Traffic Noise - The Outlook for the Future" *Proc 9th International Congress on Acoustics*, Madrid - 4-9-vii

Lay, M.G. (1985) "Source Book for Australian Roads" Australian Road Research Board - *3rd Edition of a Text Book*, February, pp 399-403

NAASRA (1974) "Roads and Traffic Noise" NAS -11, *Information of National Association of State Road Authorities* - NAASRA, Sydney, Section 31.2

NCHRP (1976) "National Cooperative Highway Research Programme" (USA)

Nelson, P. (1973) "Passenger Car and Truck Tyre Noise" *Proc Conference on Motor Vehicle Noise*, GM Desert Proving Grounds, USA, 3rd and 4th April

Moser, J. (1990) "Effects of Noise on Human Body" Graz Hygiene Institute of Austria, Proc Noise Conference, A.V.L.- GMbH, Austria, *Jrl Inst of Road Transport Engineers* (UK) September, pp 10-12

Ouay, P. (1976) "Acceptable Noise Levels" Proc ARRB Confersence - 1976, Volume 8, Session 32, pp 1-10

Richards, M.G. (1973) "Automotive Tyre Noise" A Comprehensive Experimental Study, Engineering Publication A - 2973, GM Proving ground, *Proc National Noise and Vibration Control Conference*, Chicago (iii), USA, September

Salt, G.T. (1979) "Skid Resistant Road Surfacing and Tyre Noise" *Proc Conference of Inst of Civil Engineers (UK)*, Part (i), 66, February

Samuels, S.E. (1986) "Traffic Noise Measurements and Prediction Practices in Australia" *Proc 13th ARRB Conference*, 13(2), pp 30-37

Samuels, S.E (1976) "Traffic Noise - A Study of a Tyre/Road Mechanism" *Proc ARRB Conference - 1976*, Volume 8, Session 33, pp 1-7

Sandberg, U.L.F. (1987) "Road Traffic Noise - the Influence of the Road Surface and its Characterisation" Applied Acoustics, Vol 21, pp 112.

Saunders, R.E. (1986) "Traffic Noise and Road Design" *Proc Seminar on Noise and Vibration Control*, Arranged Soc of Automotive Engineers, Australasia, Melbourne, July

Saunders, R.E and Jameson, G.W. (1978) "An Approach to Traffic Noise Studies" *Proc 9th ARRB Conference*, 9(6), pp 240-247

Schubert, G (1990) "Noise Attenuation Developments for major Transport Corridor Projects" Australian Road Research Board (ARRB), *Proc 15th ARRB Conference*, Part 7, pp 282-284

Snow, R and Law, R. (1978) "Motor Vehicle Control Legislation in Australia" *Professional Paper No: 780384*, Society of Automotive Engineers (USA)

Stone, G and Saunders, R.E. (1982) "The Use of Traffic Noise Barriers by the Country Roads Board, Victoria, *Proc 11th ARRB Conference*, 11(6), pp 115-125

Taylor, M.A.P and Young, W. (1988) "Traffic Analysis - New Technology and New Solutions" *Source Book by Hargreen Publishing Company*, Australia, p 289

Tetlo, D (1973) "Passenger Car and Truck Tyre Noise" *Proc Conference on Motor Vehicle Noise*, GM Desert Proving Grounds, USA, April, 3rd and 4th

Trivissnno, N.M and Beatty , J.R. (1967) "The Origin of Tyre Squeal" *Report of Kautchuk and Gummi,* USA, January

TRRL (1970) "Working Group on Research into Road Traffic Noise" *Review Report No: LR-357 on Road Traffic Noise*, Transport and Road Research Laboratory, Crowthorne (UK)

Turner, J.D., and Pretlove, A.J. (1991) "Acoustics for Engineers" *A source book in Acoustical Engineering by Macmilan Education Limited*, London, pp 8-73

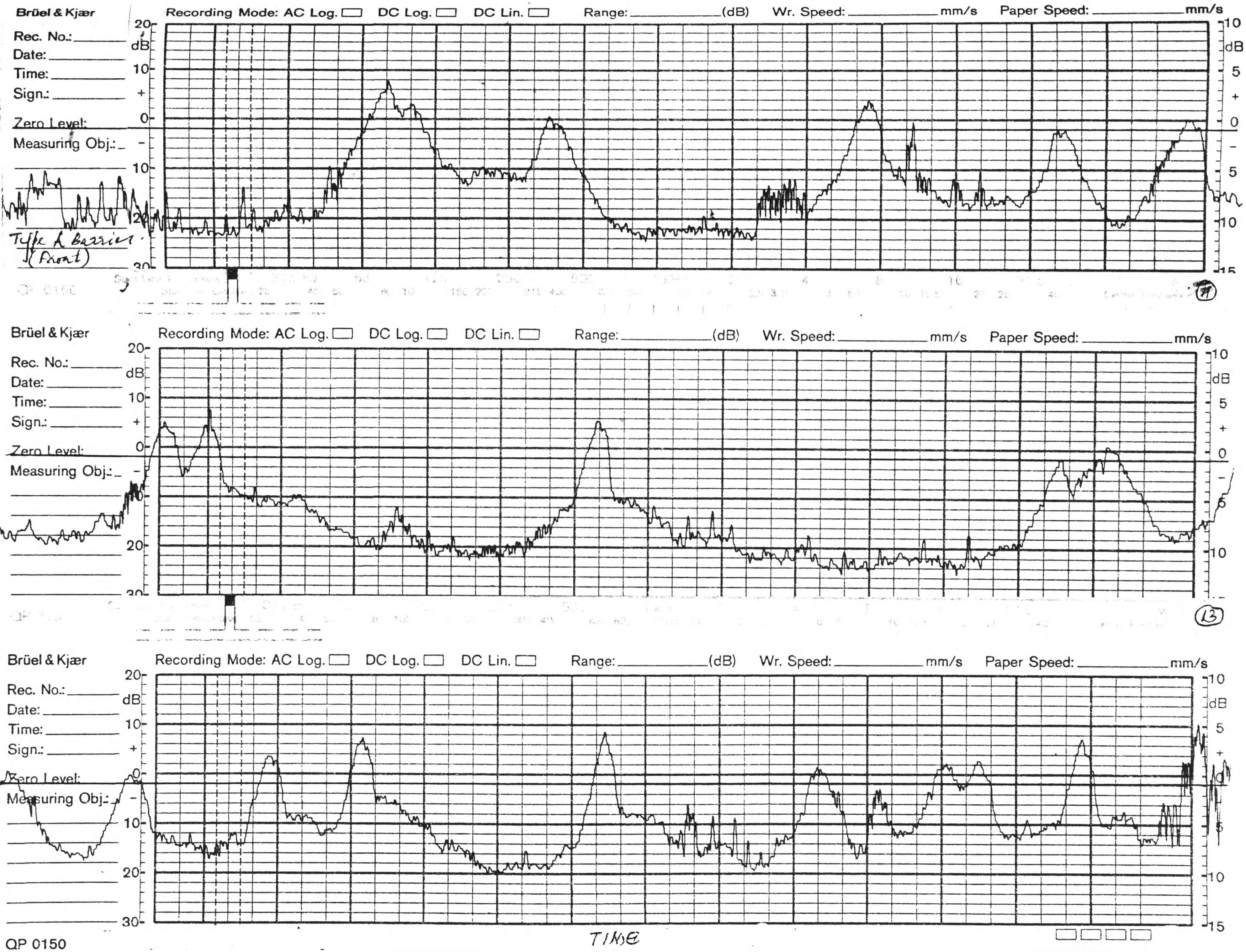
USEPA (1974) "Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety" United States Environment Protection Authority, *Paper No: EPA 550/9-74-004*, Washington, USA

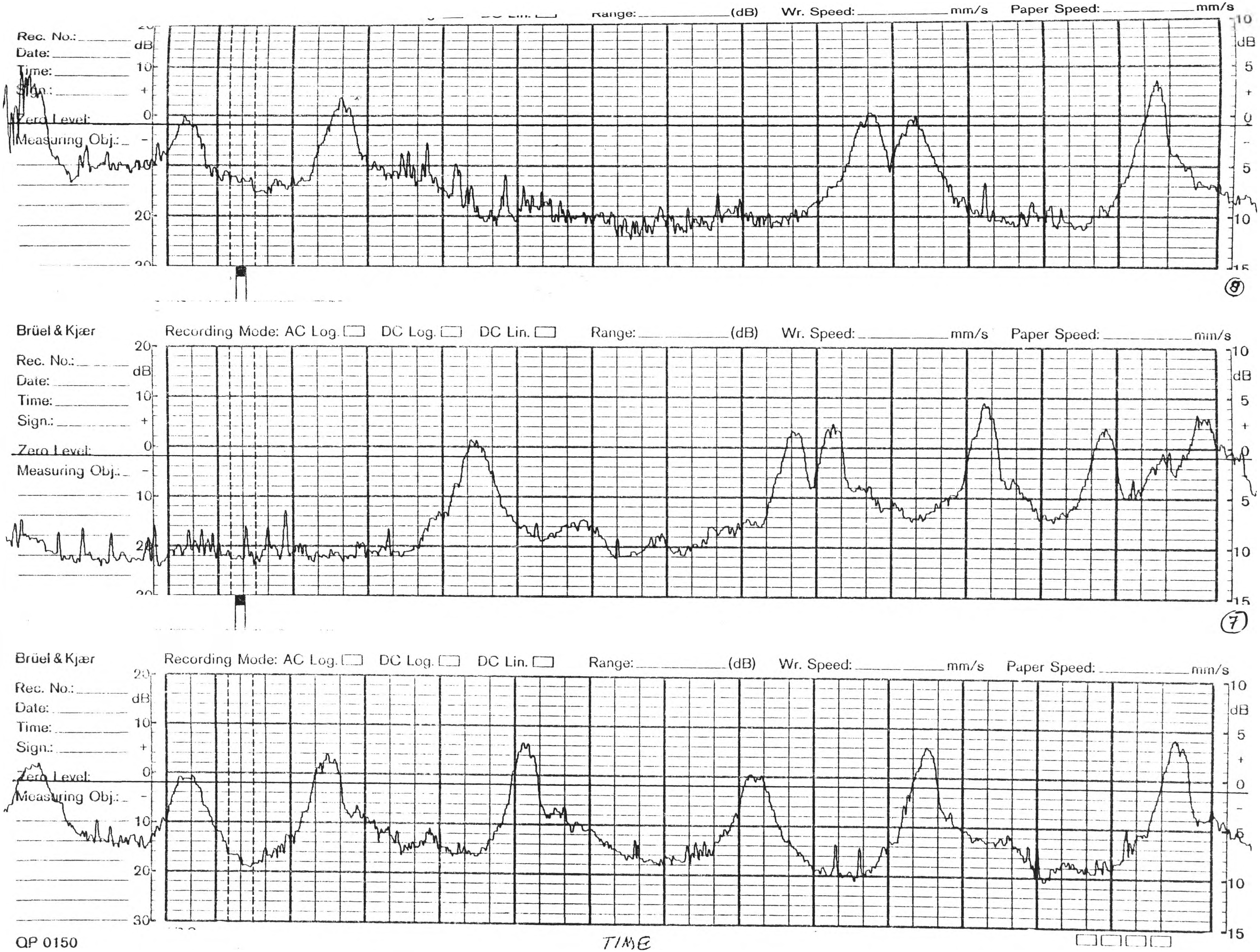
Watkins, L.H. (1974) "A Quiet Heavy Lorry" *Report of a TRRL and DoE Sponsored Quiet Heavy Vehicle Development Project*, Crowthorne, Berkshire, UK.

APPENDICES

APPENDIX 1

Test results of noise barrier surveys - Type "A" barrier (without)





Test results of noise barrier surveys - Type "A" barrier (without)

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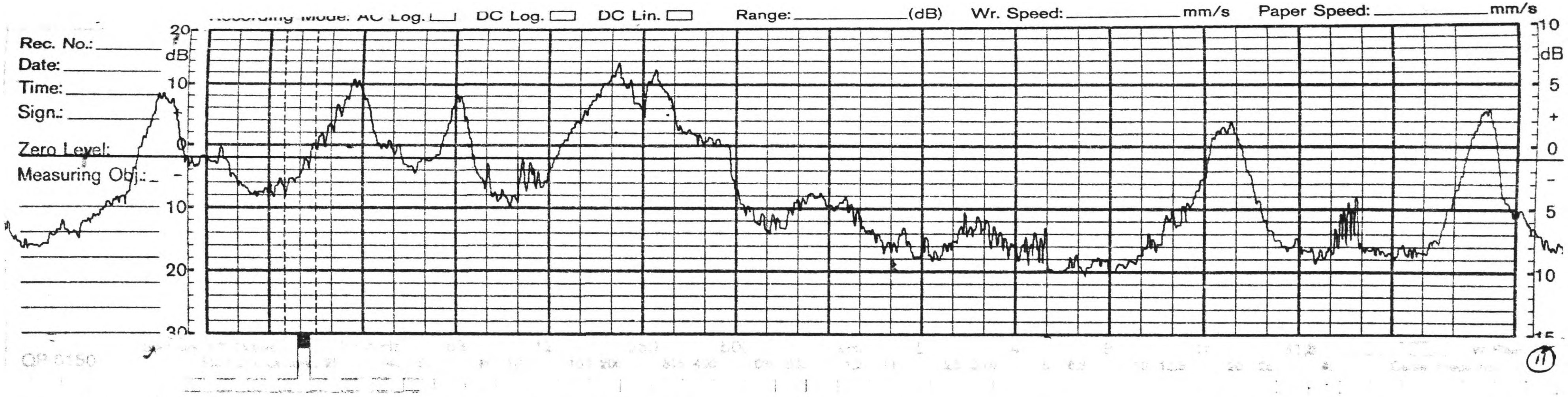

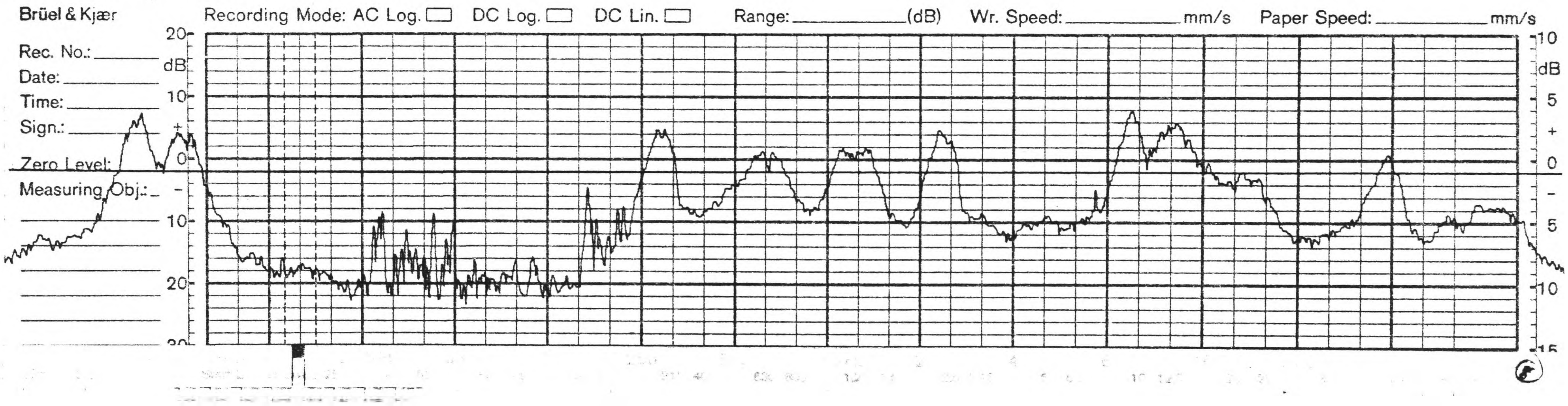

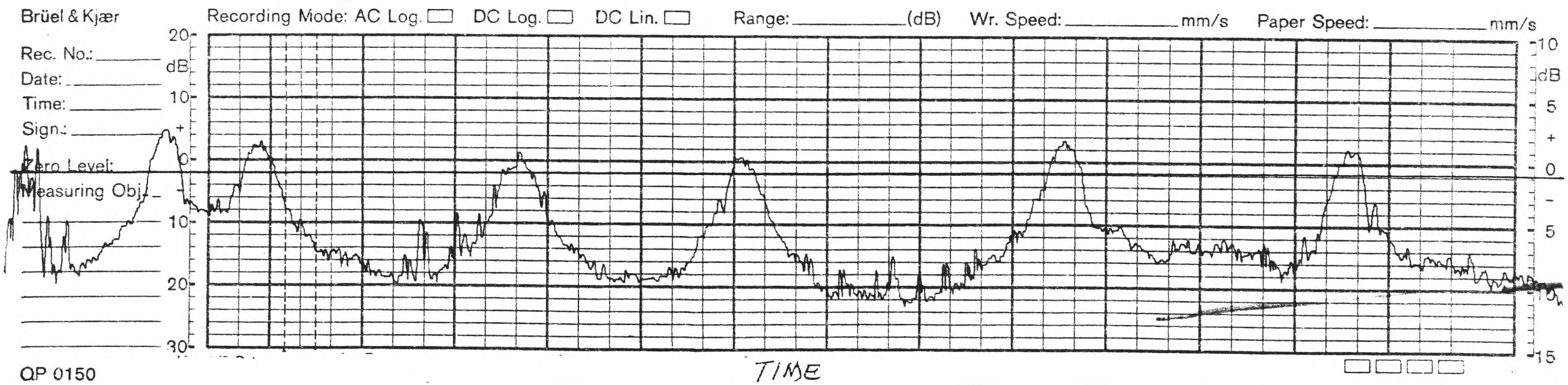

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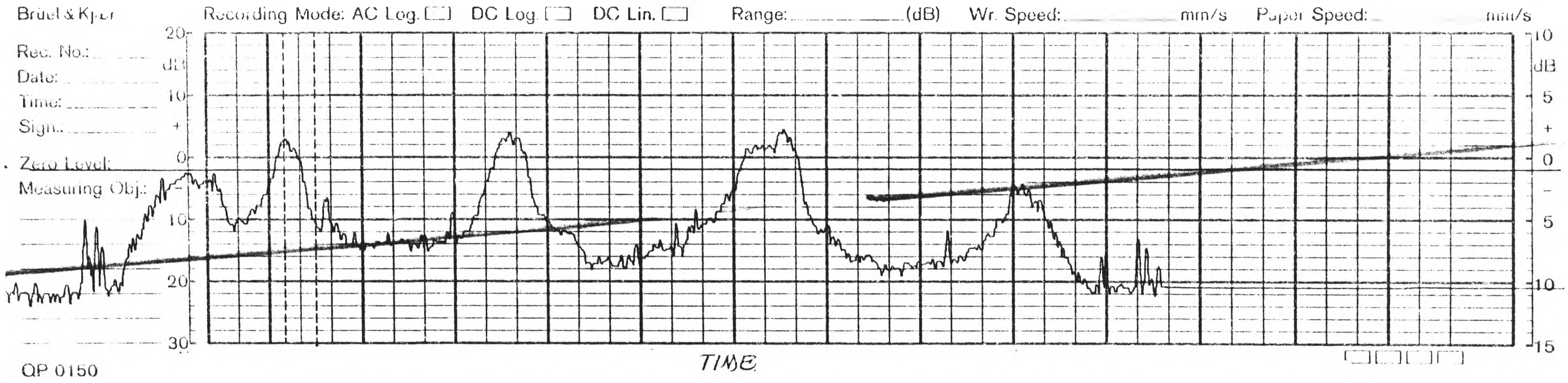

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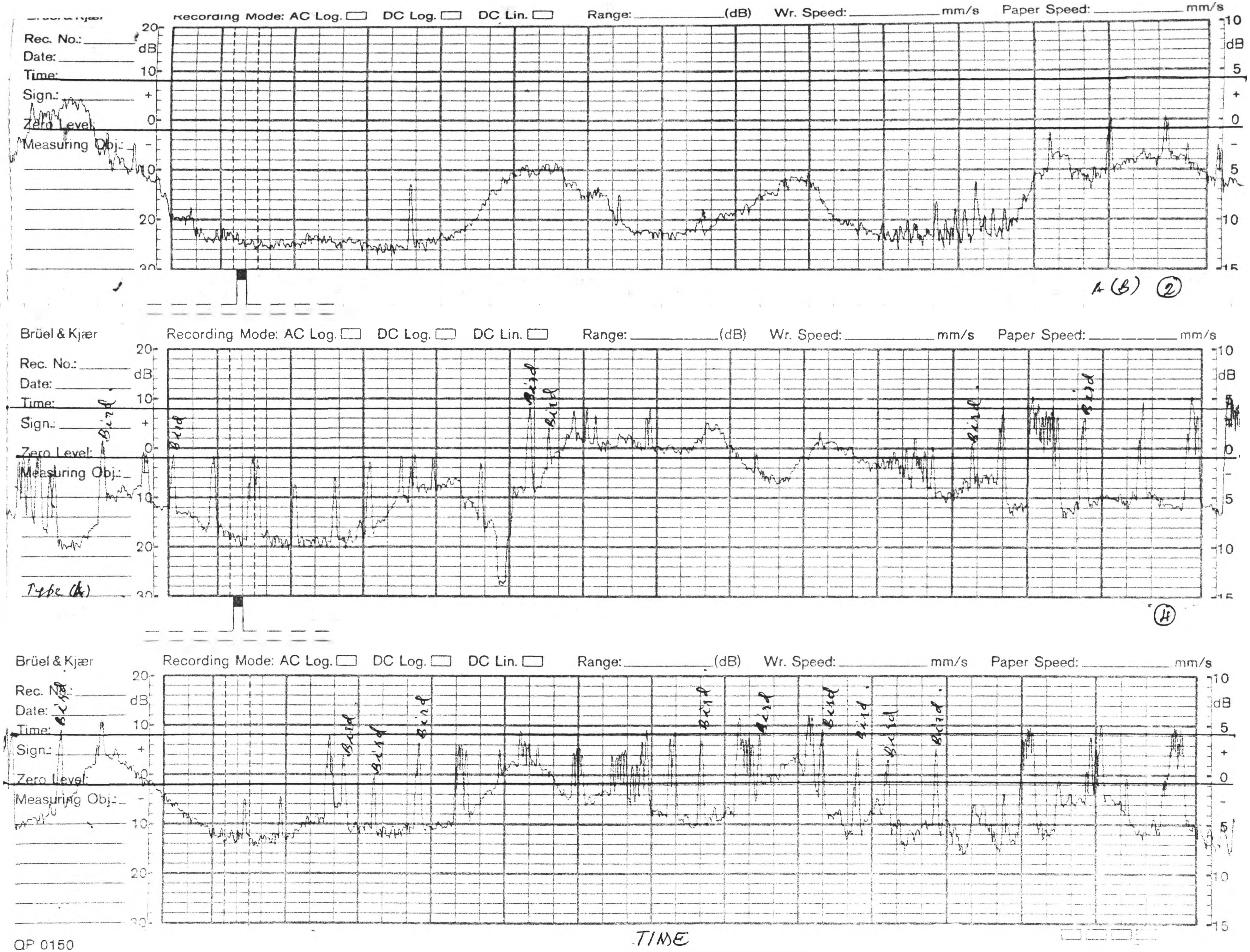

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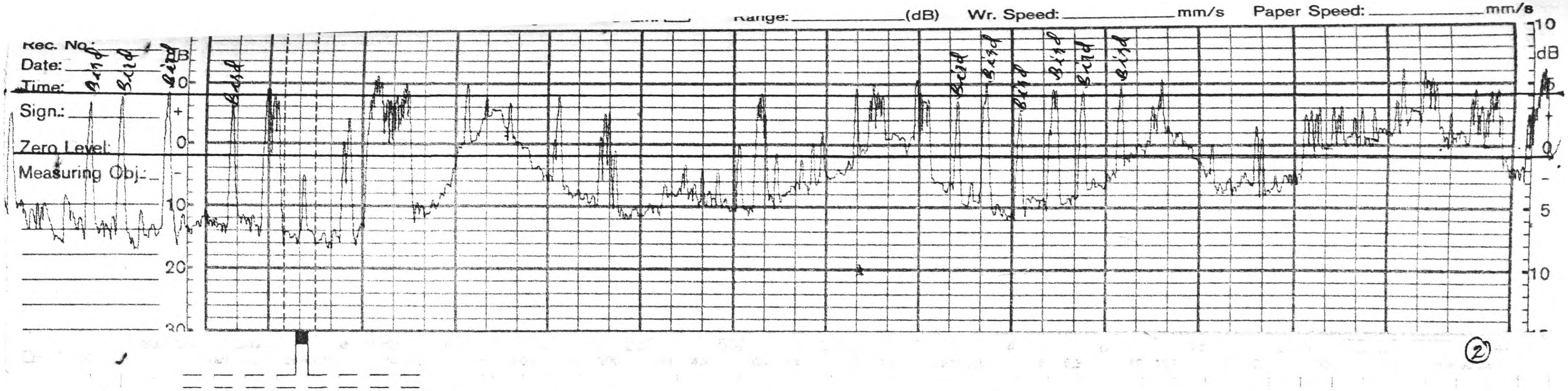

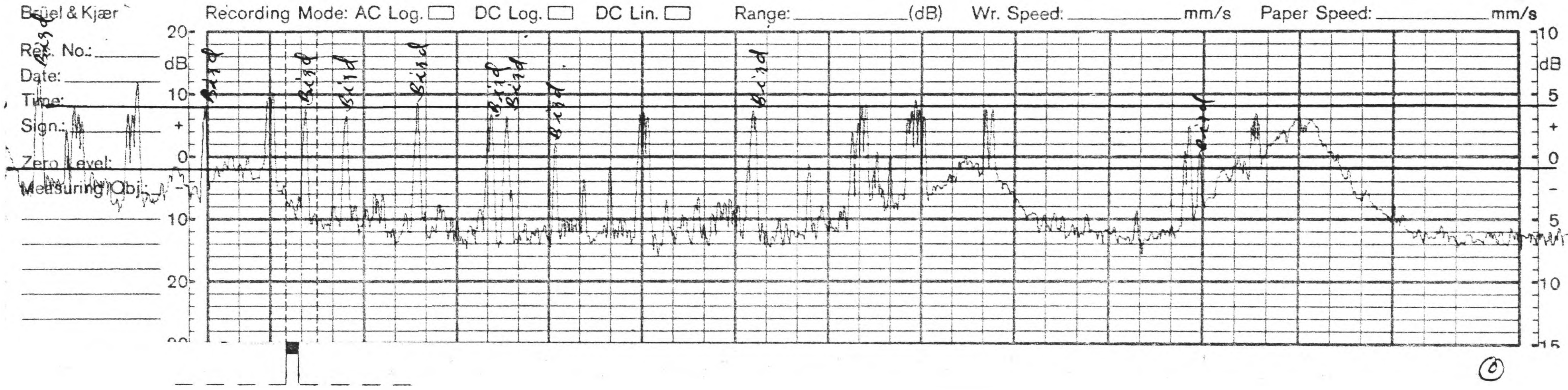

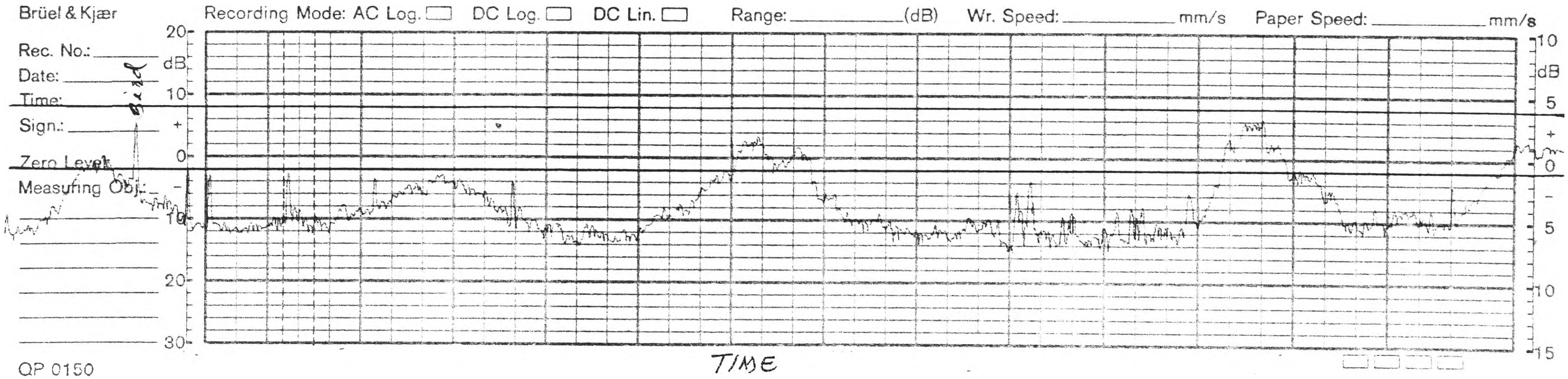

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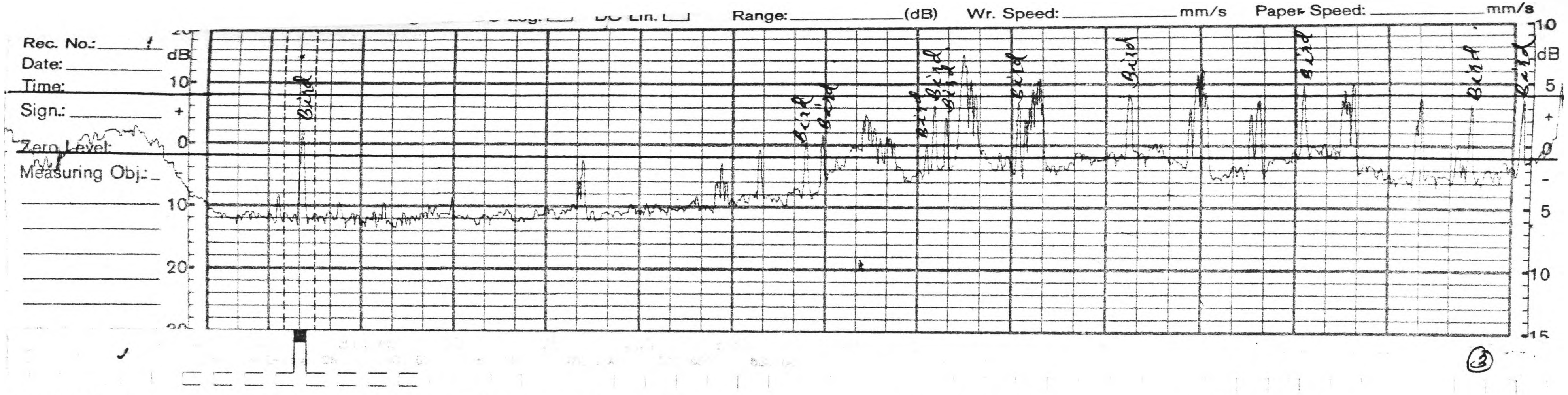
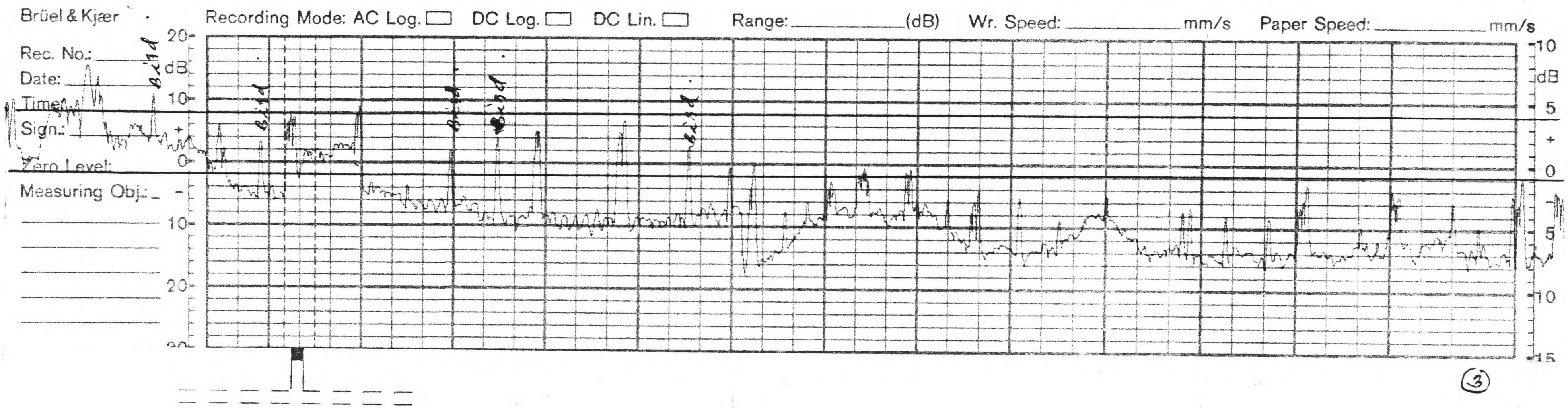
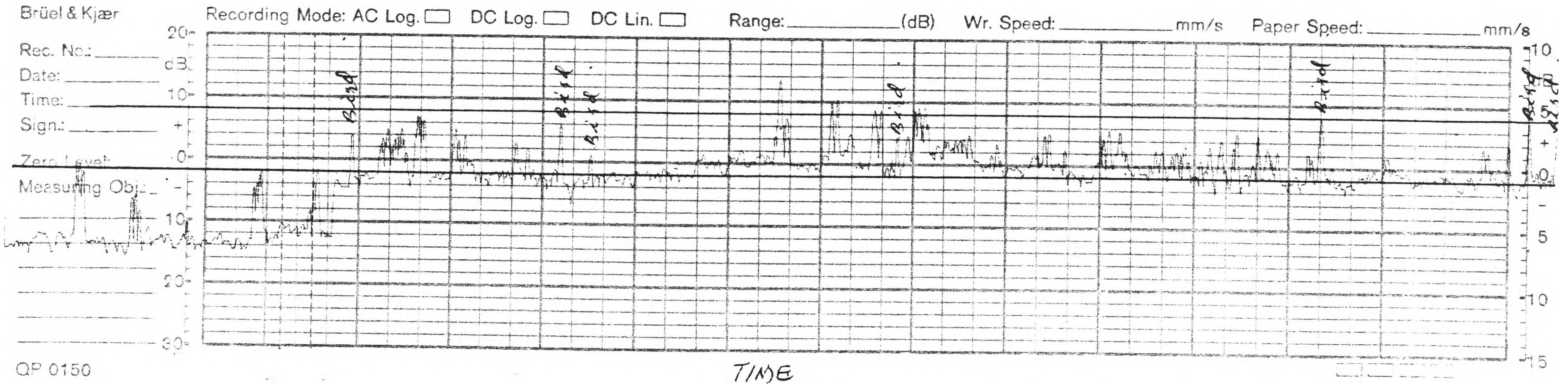
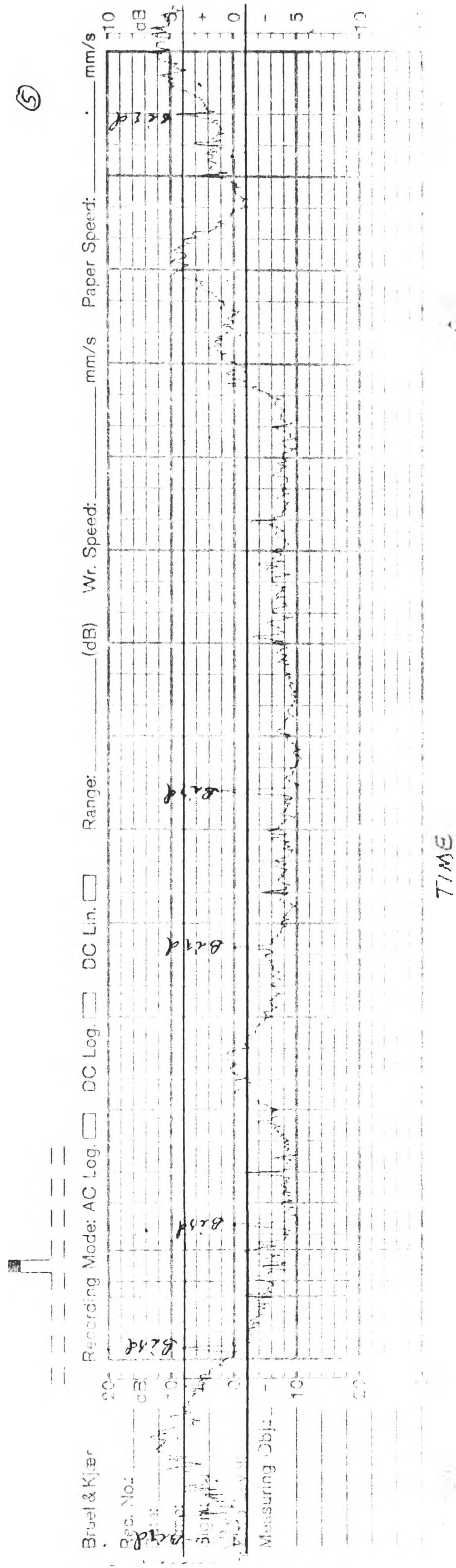
Contd: Test results of Type "A" barrier (with)









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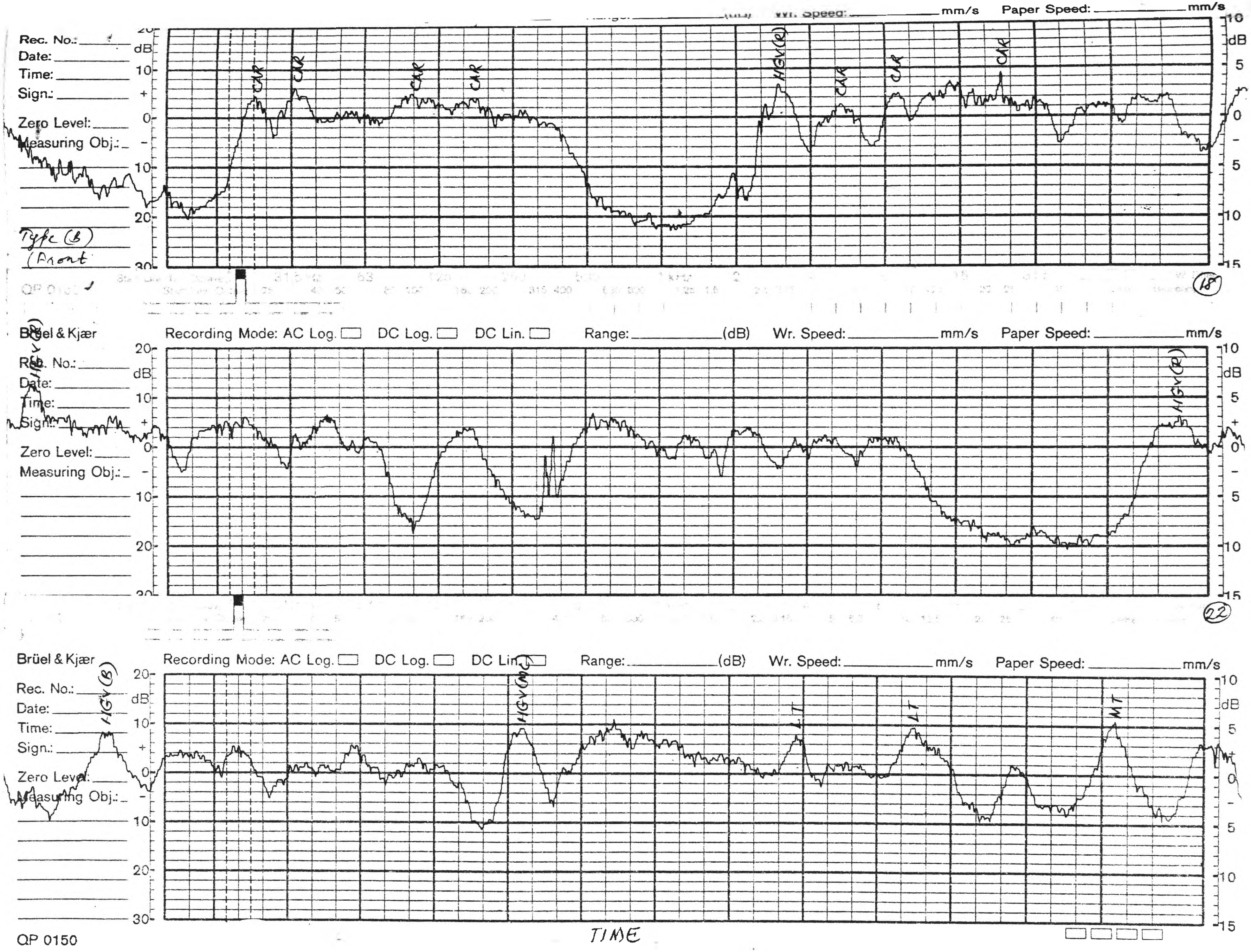
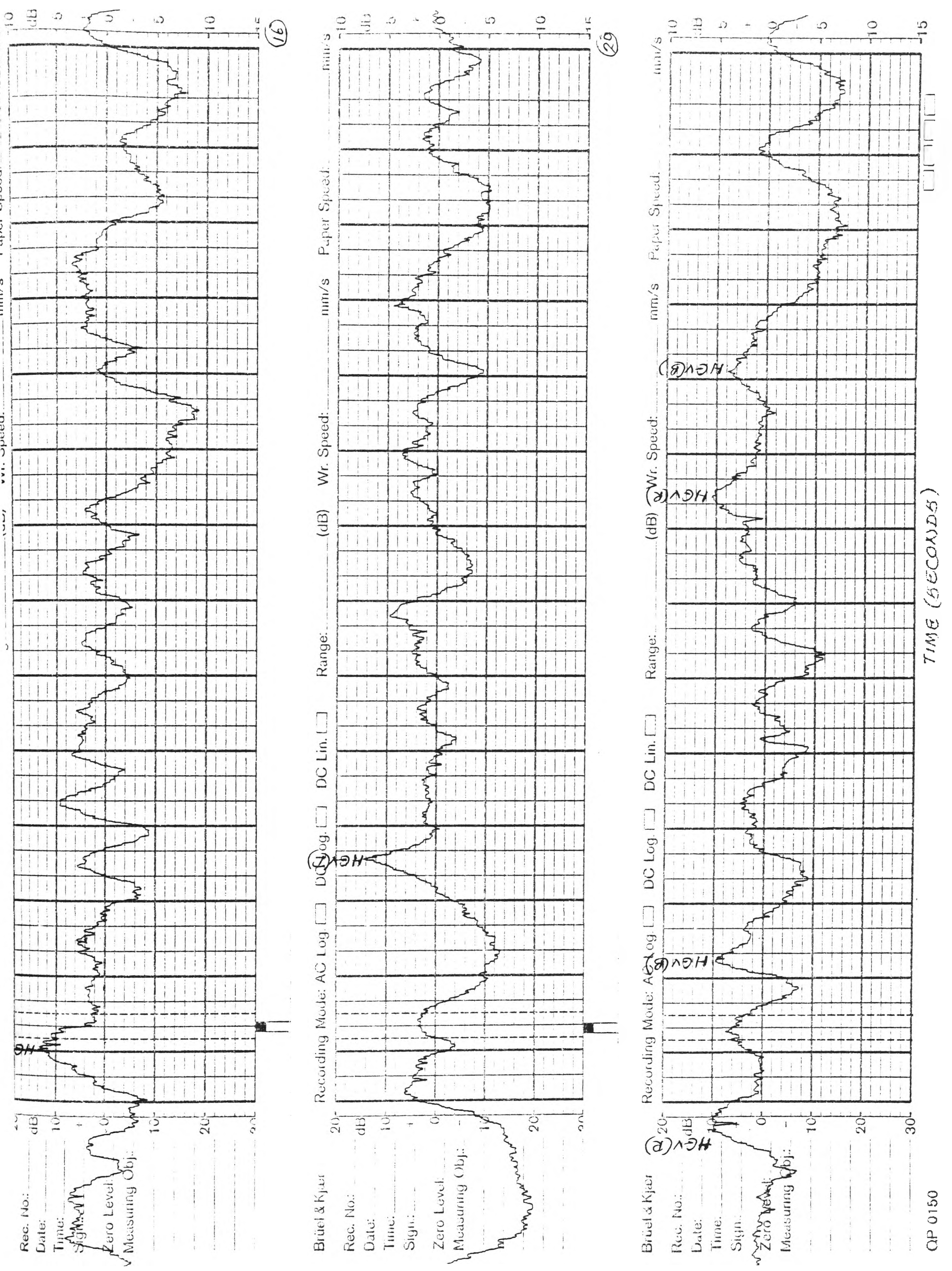


Test results of Type "B" barrier (without)



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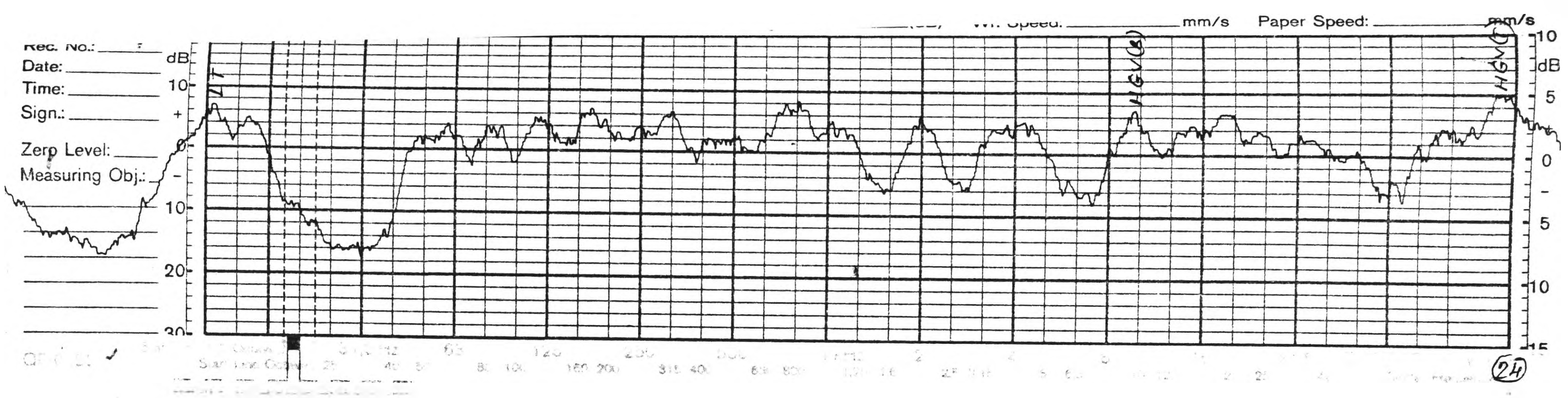
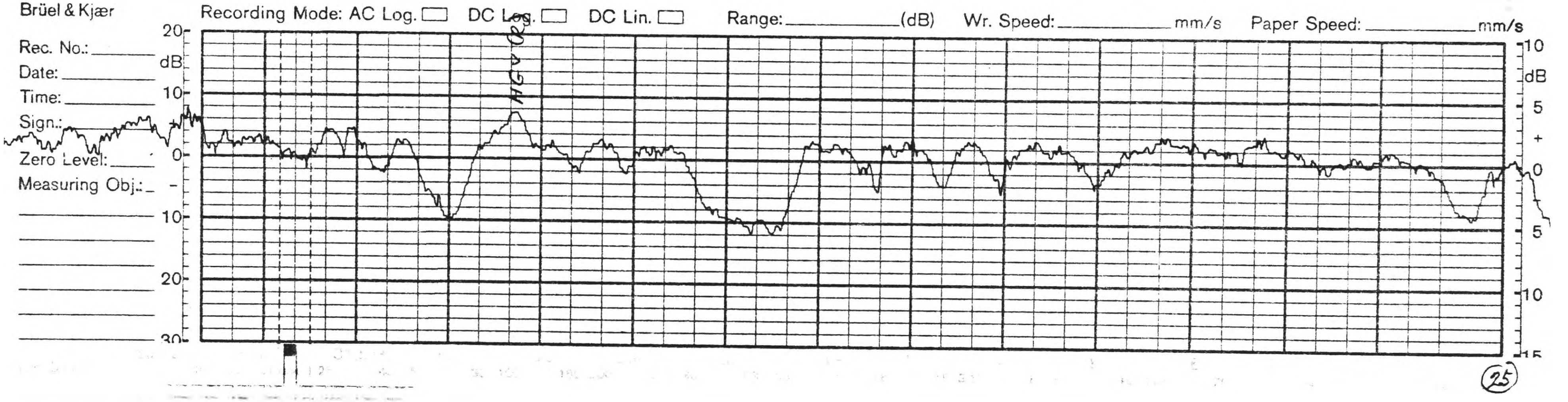
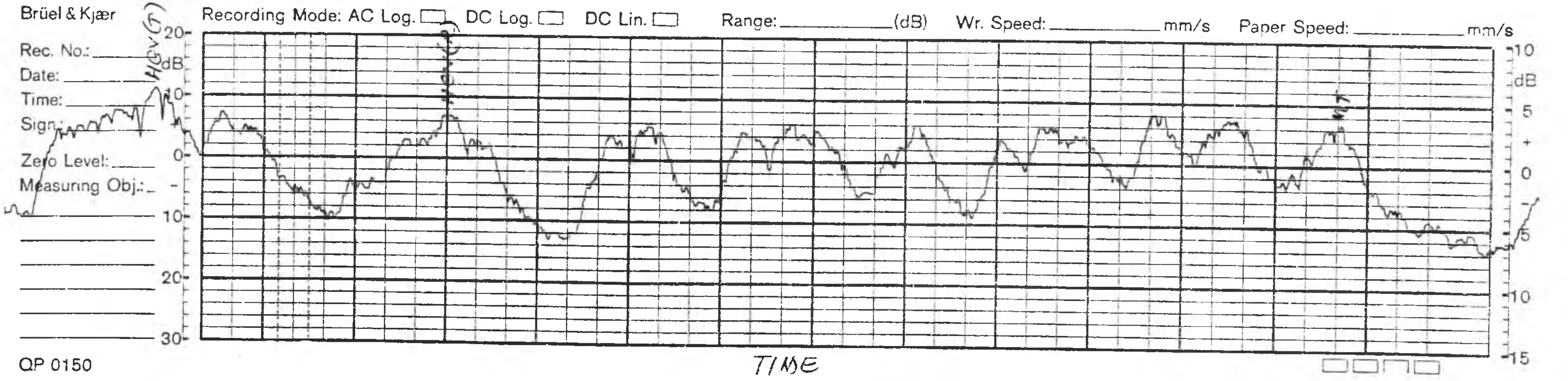
Contd: Test results of Type "B" barrier (without)







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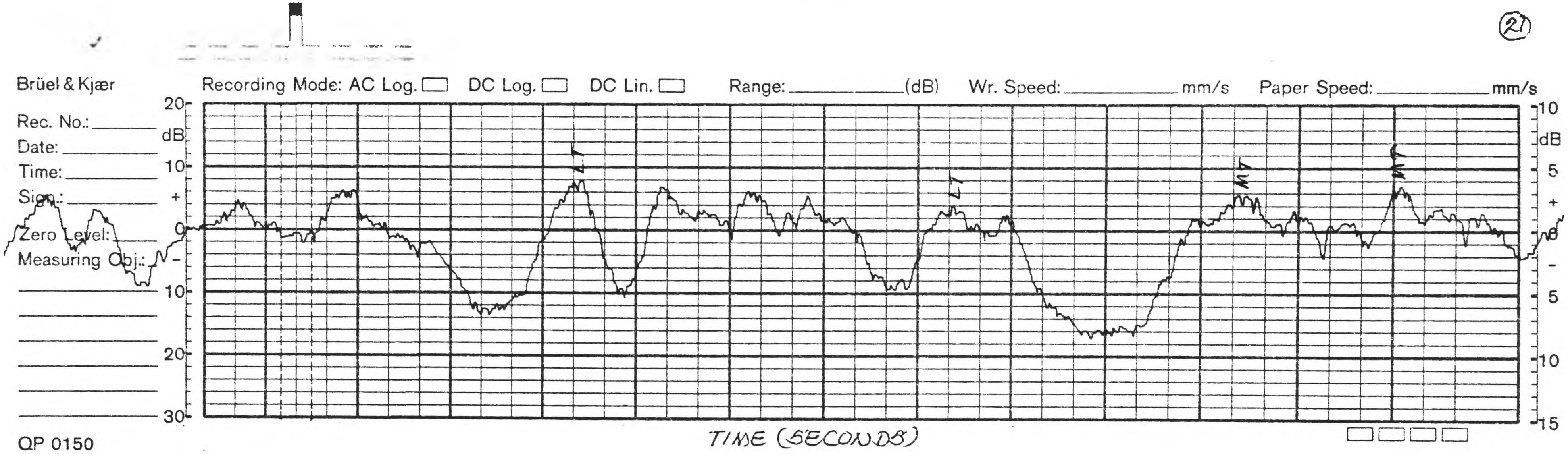

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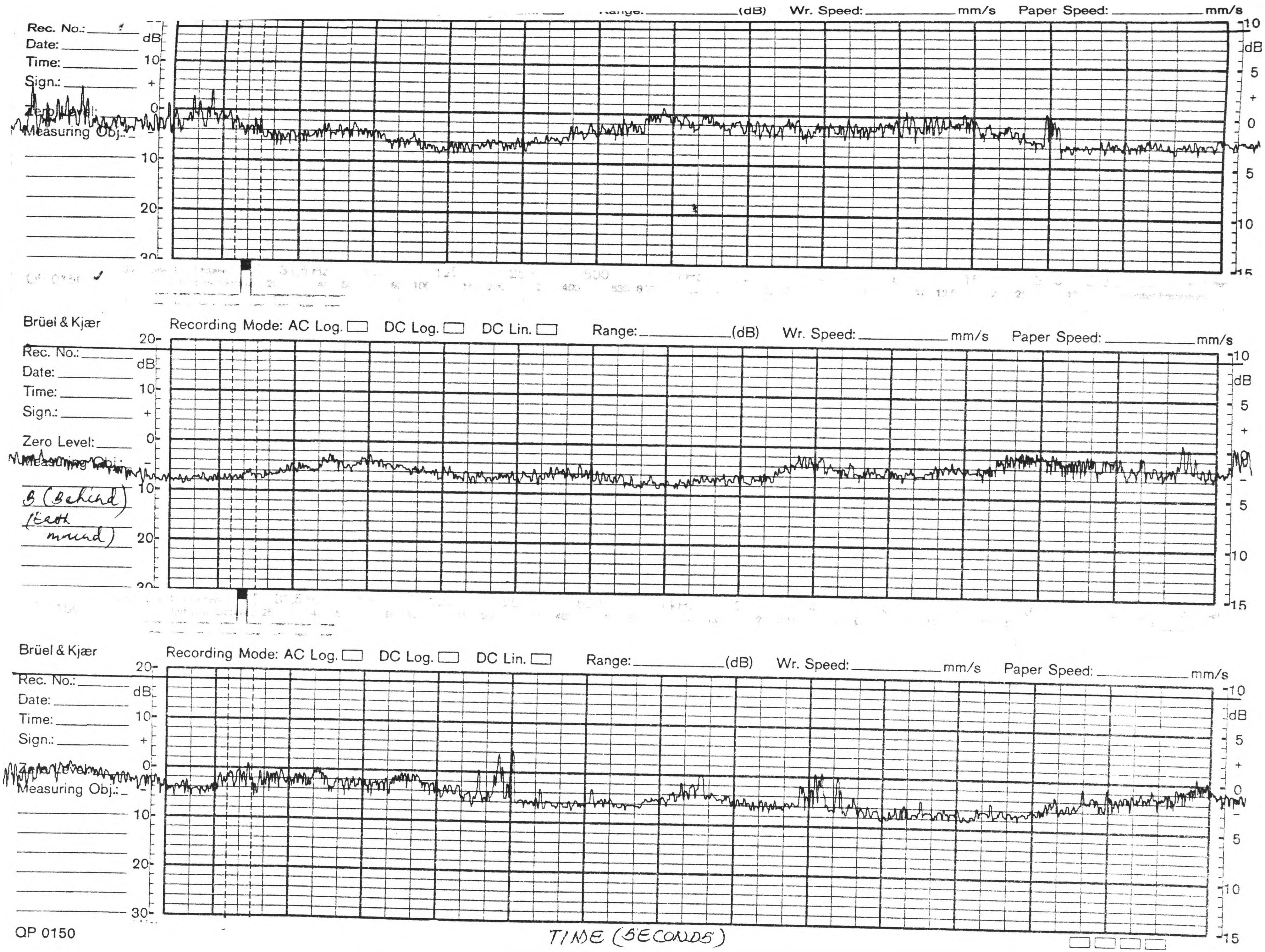

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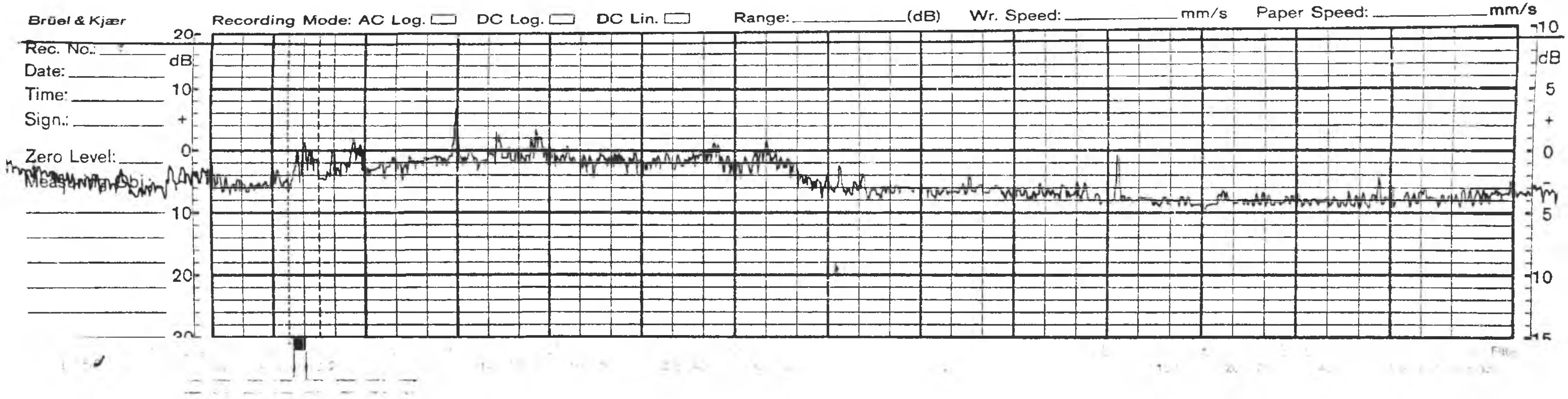

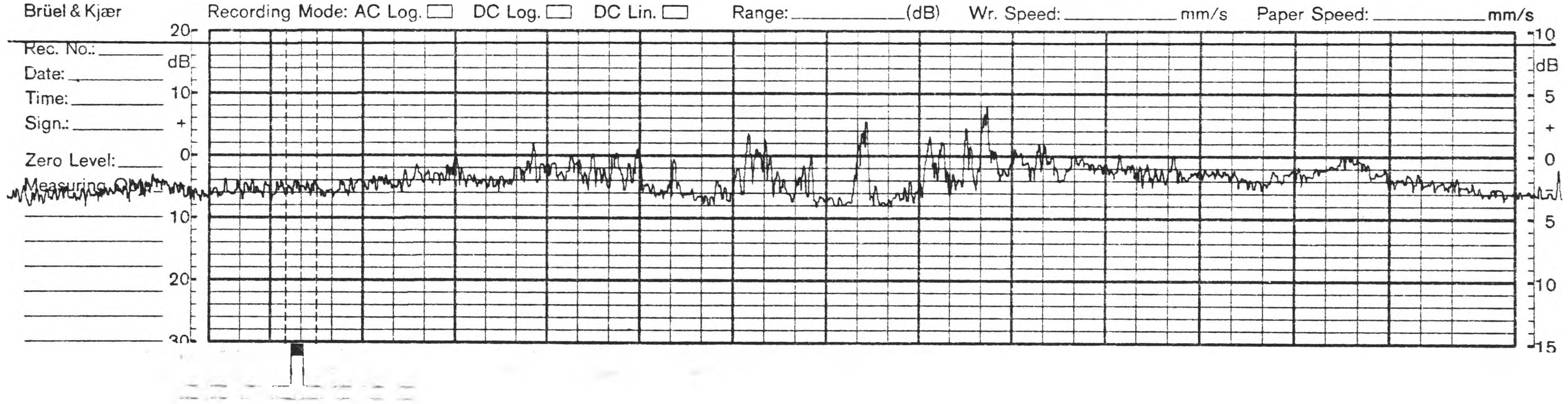

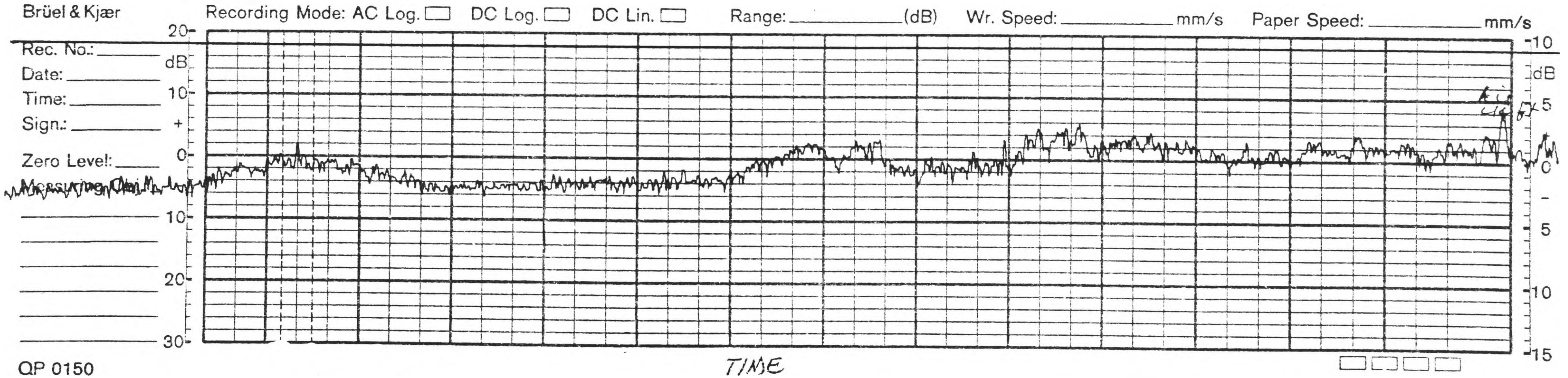

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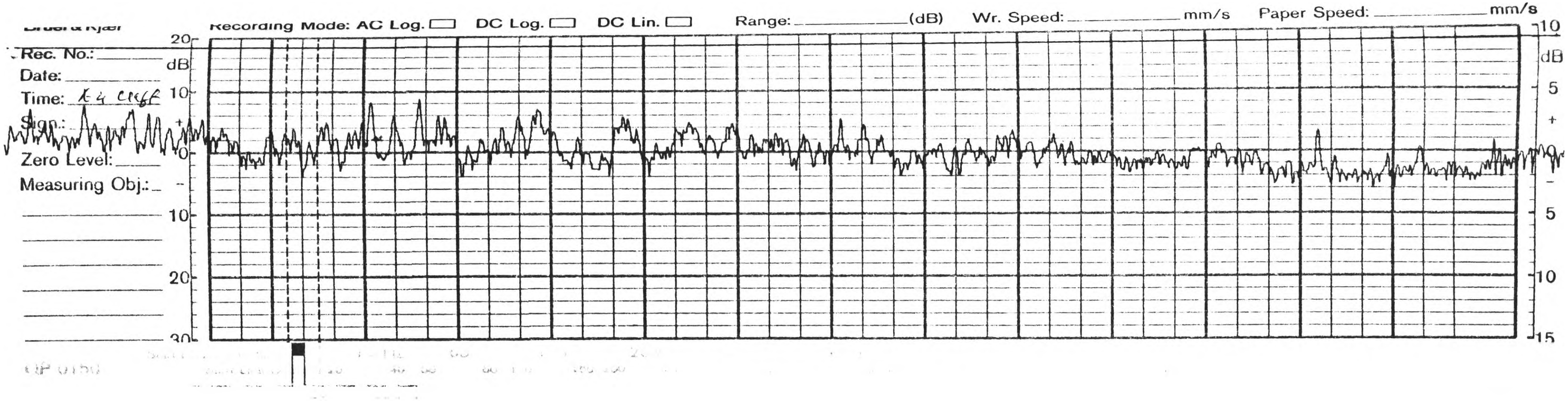
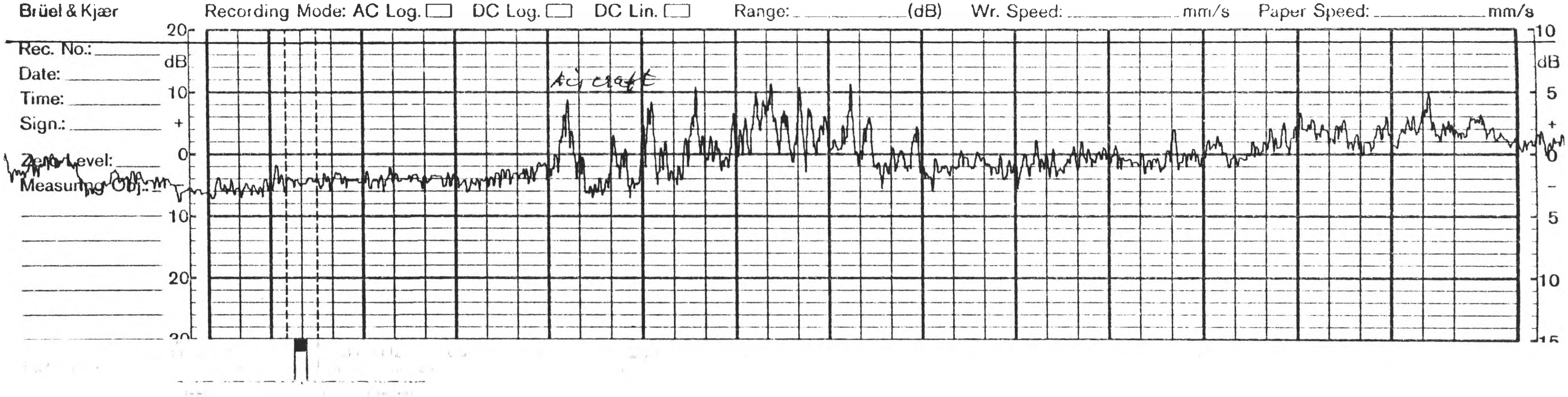
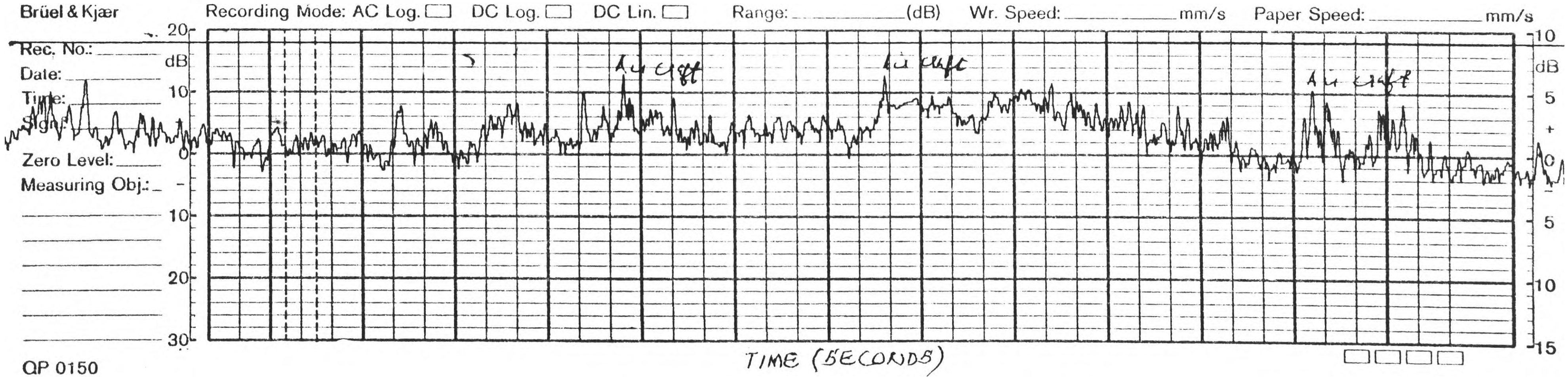
Contd: Test results of Type "B" barrier (with)







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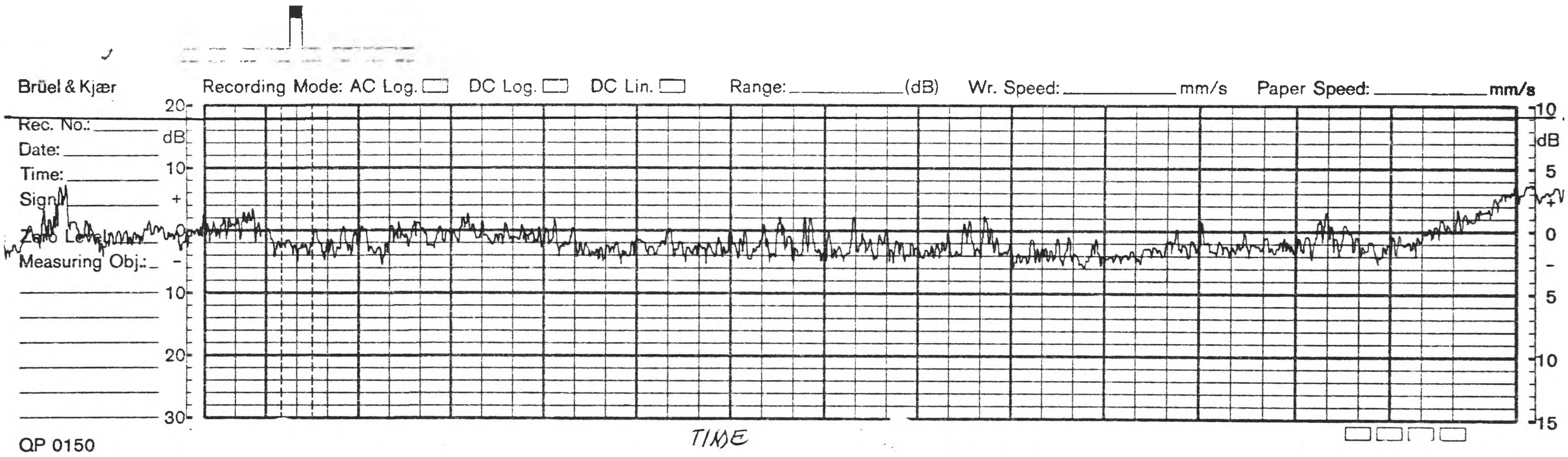
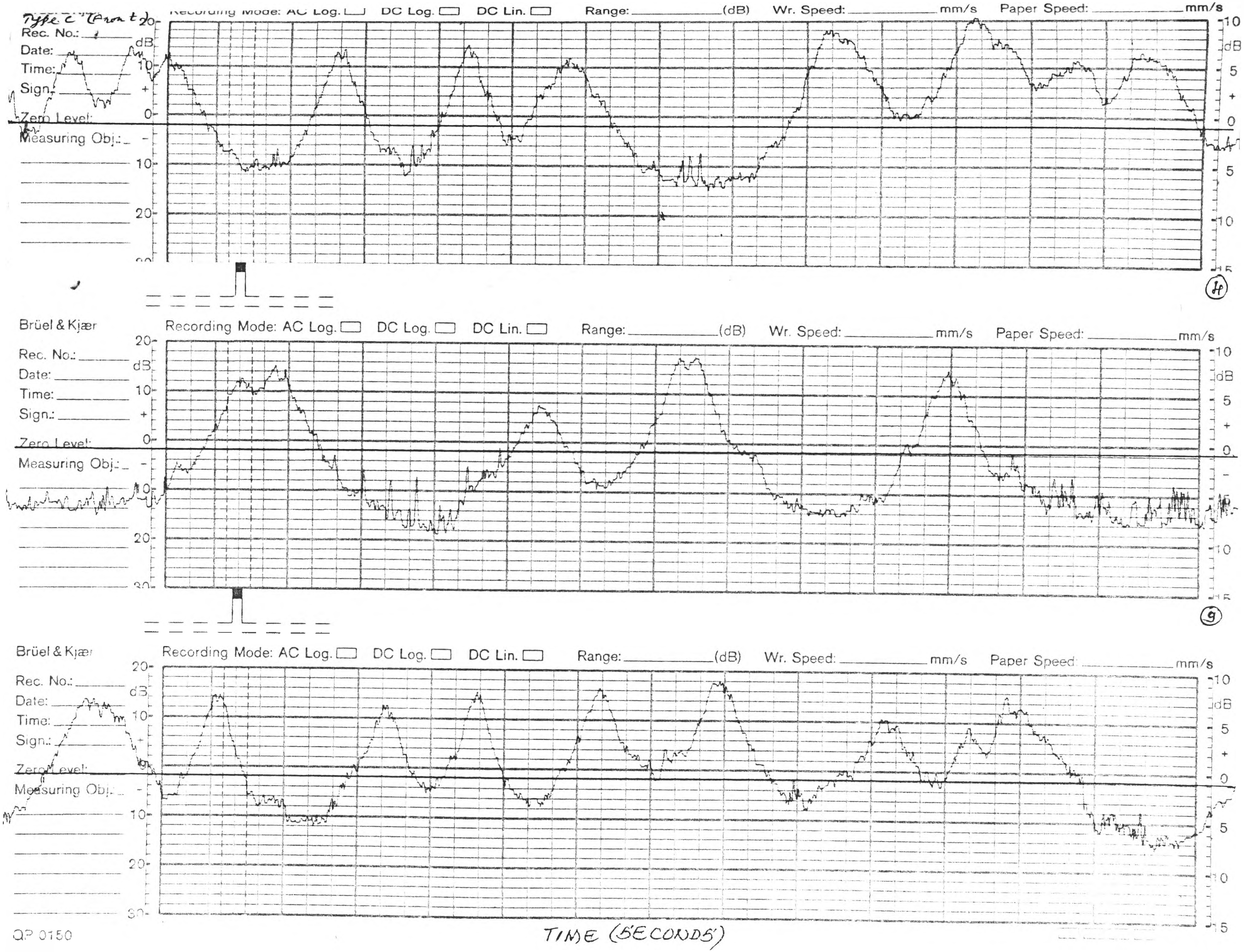
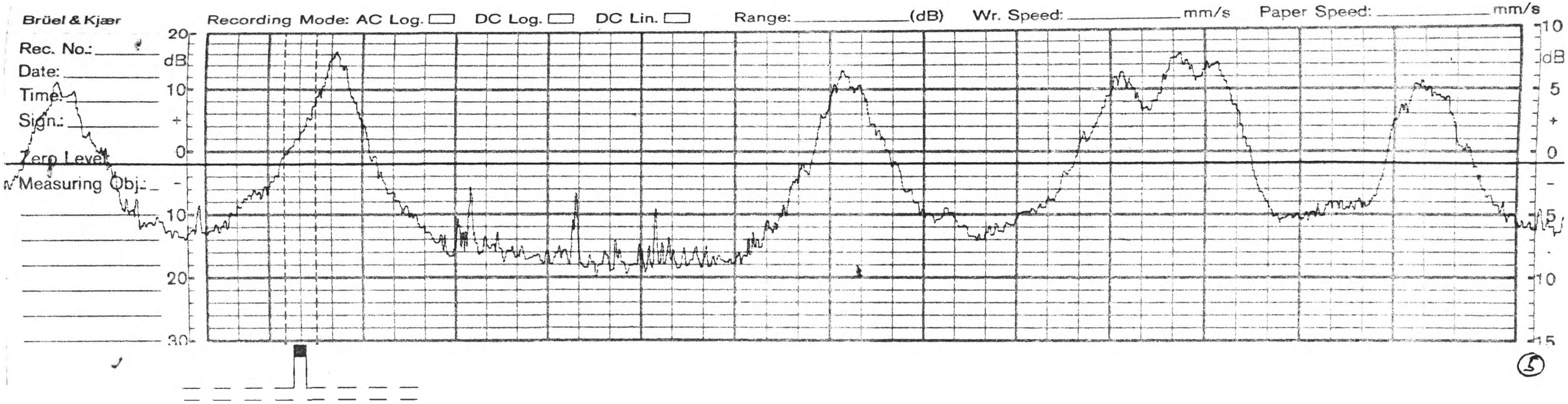
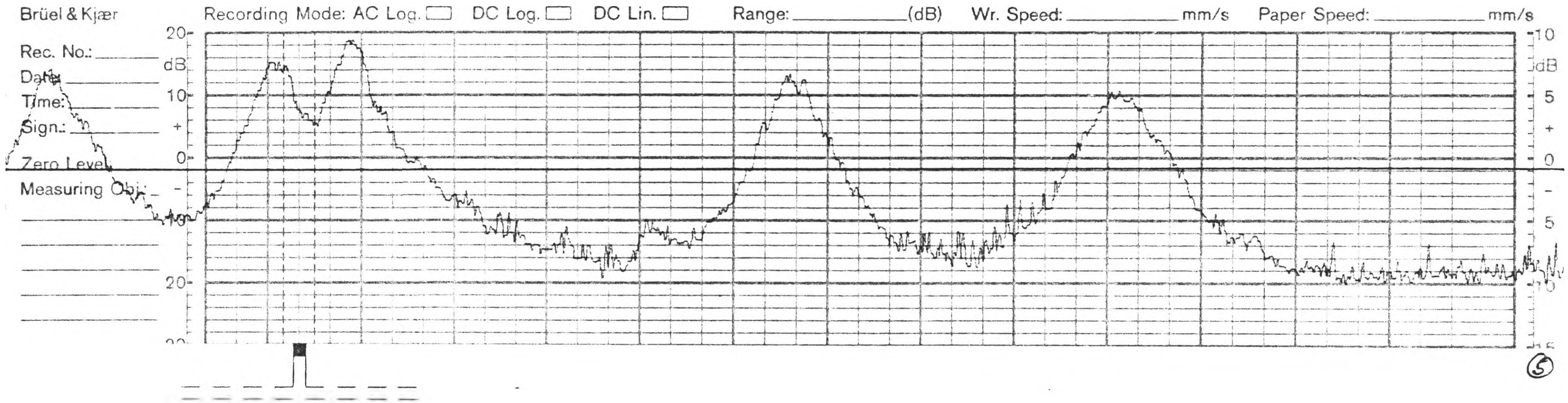
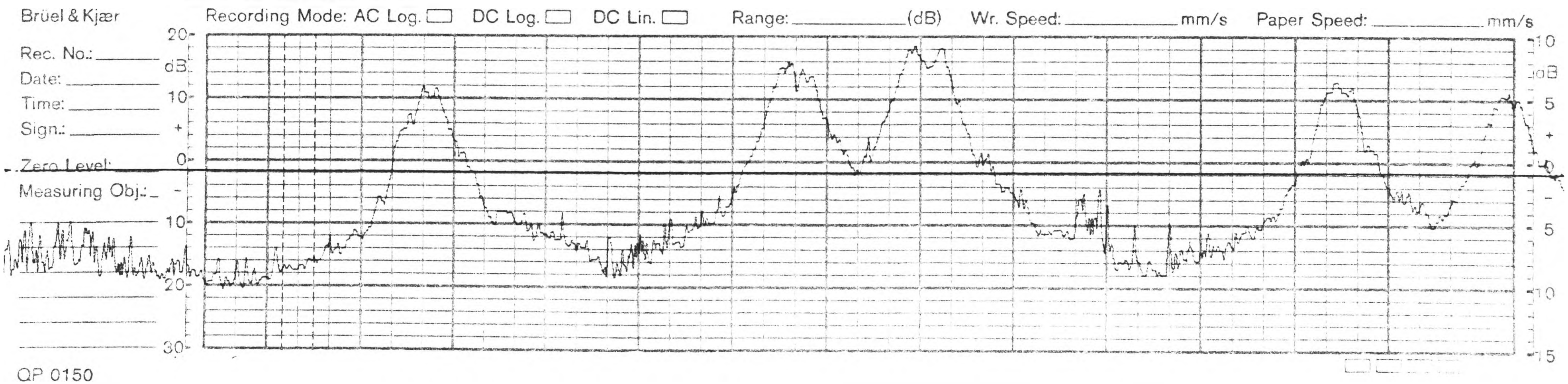




Test results of Type "C" barrier (without)







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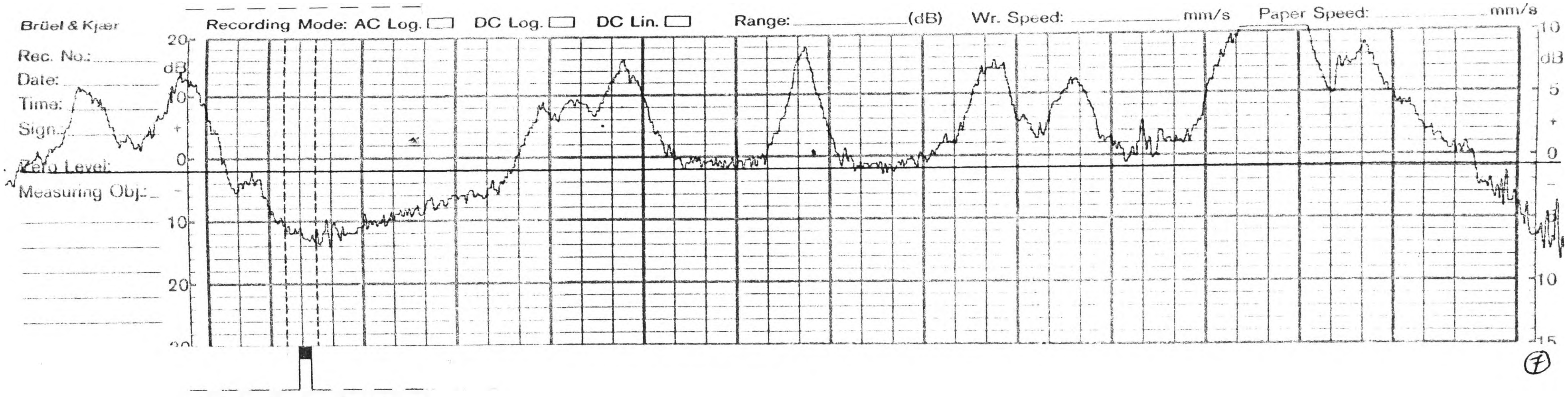

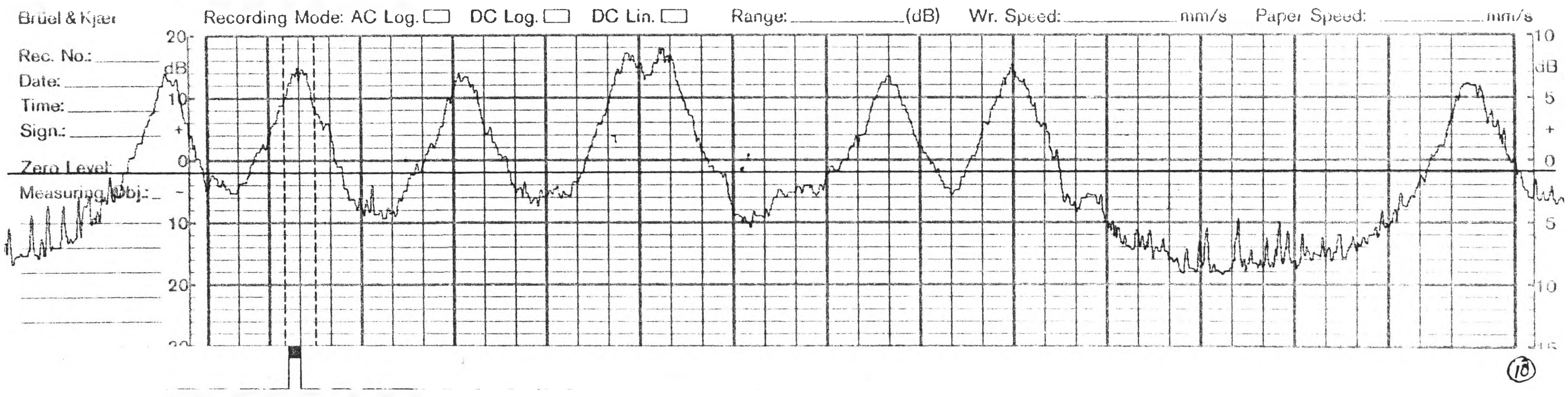

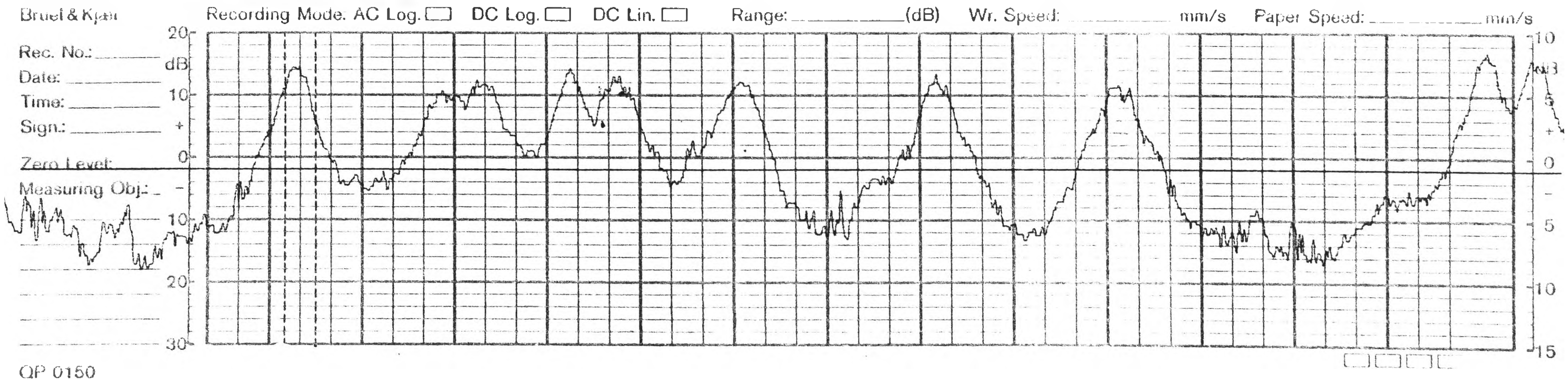

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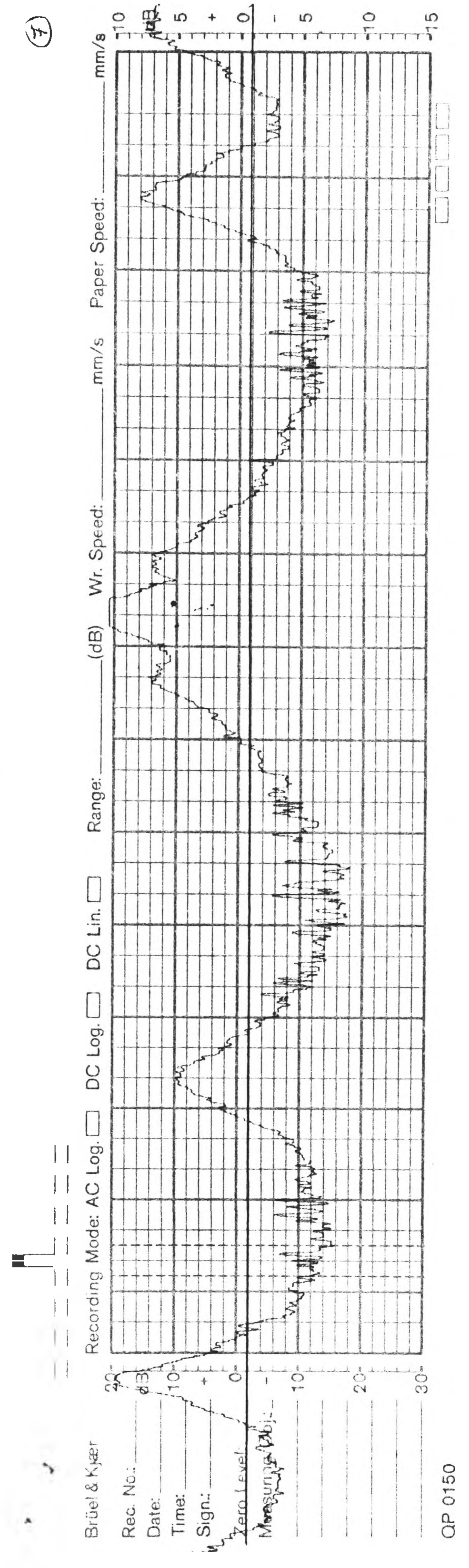

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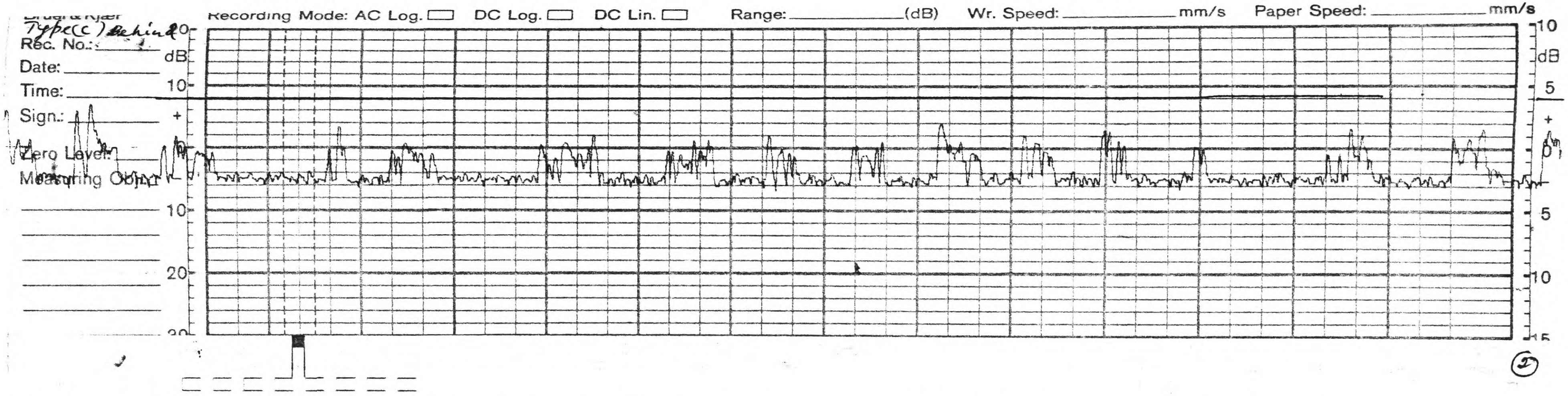

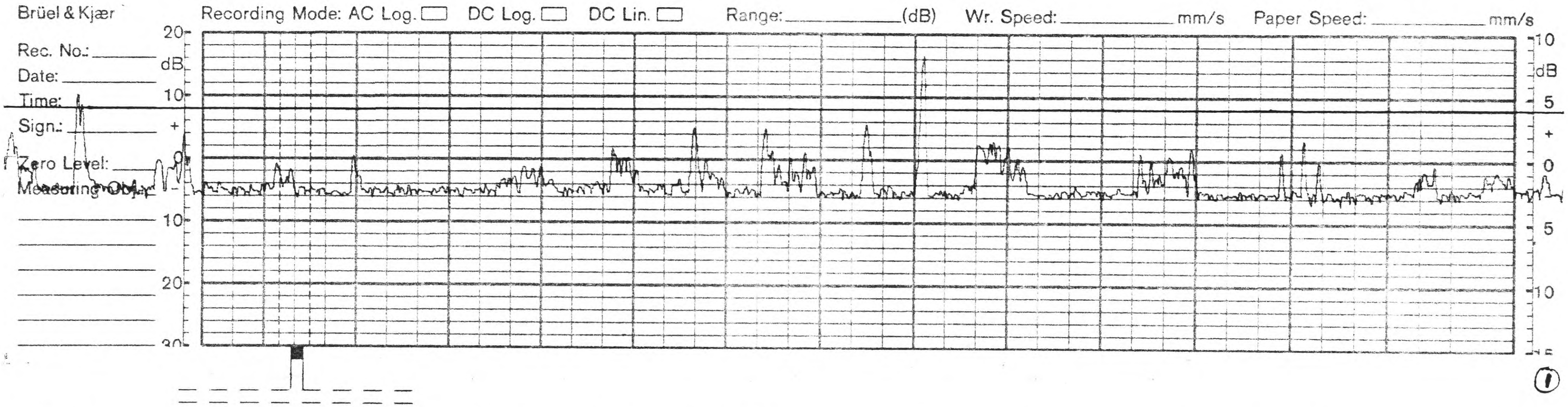

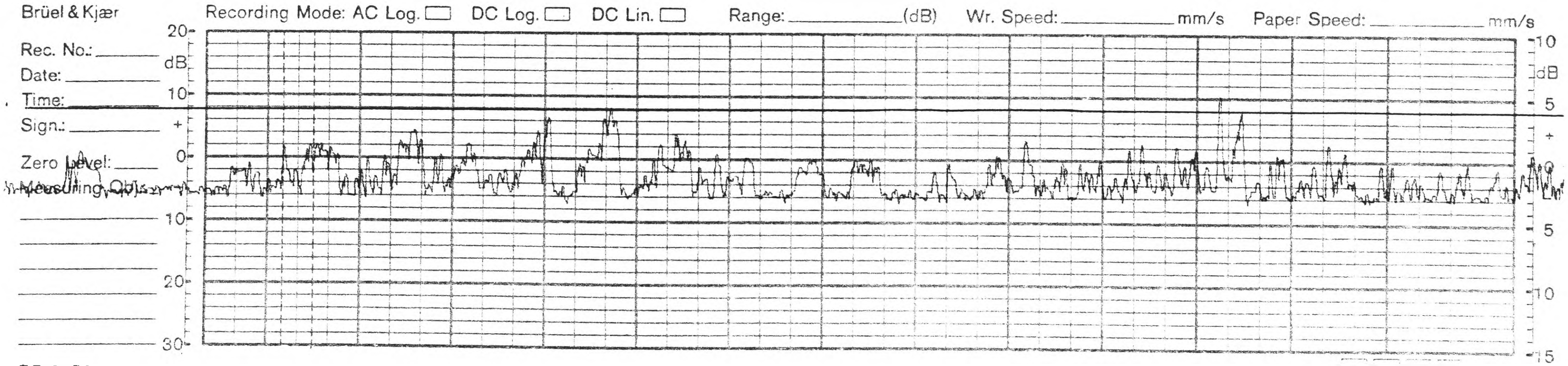

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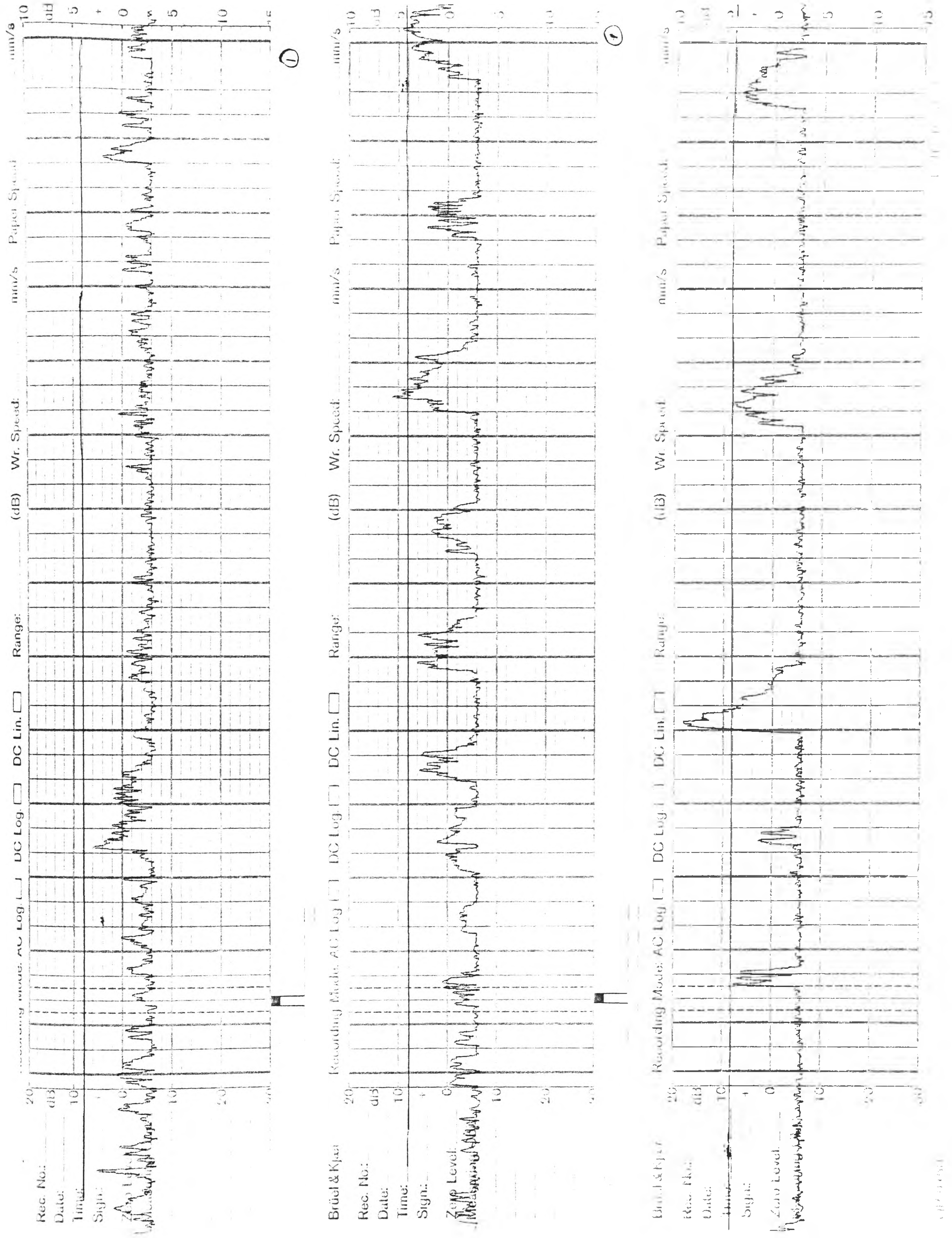
Test results of Type "C" barrier (with)



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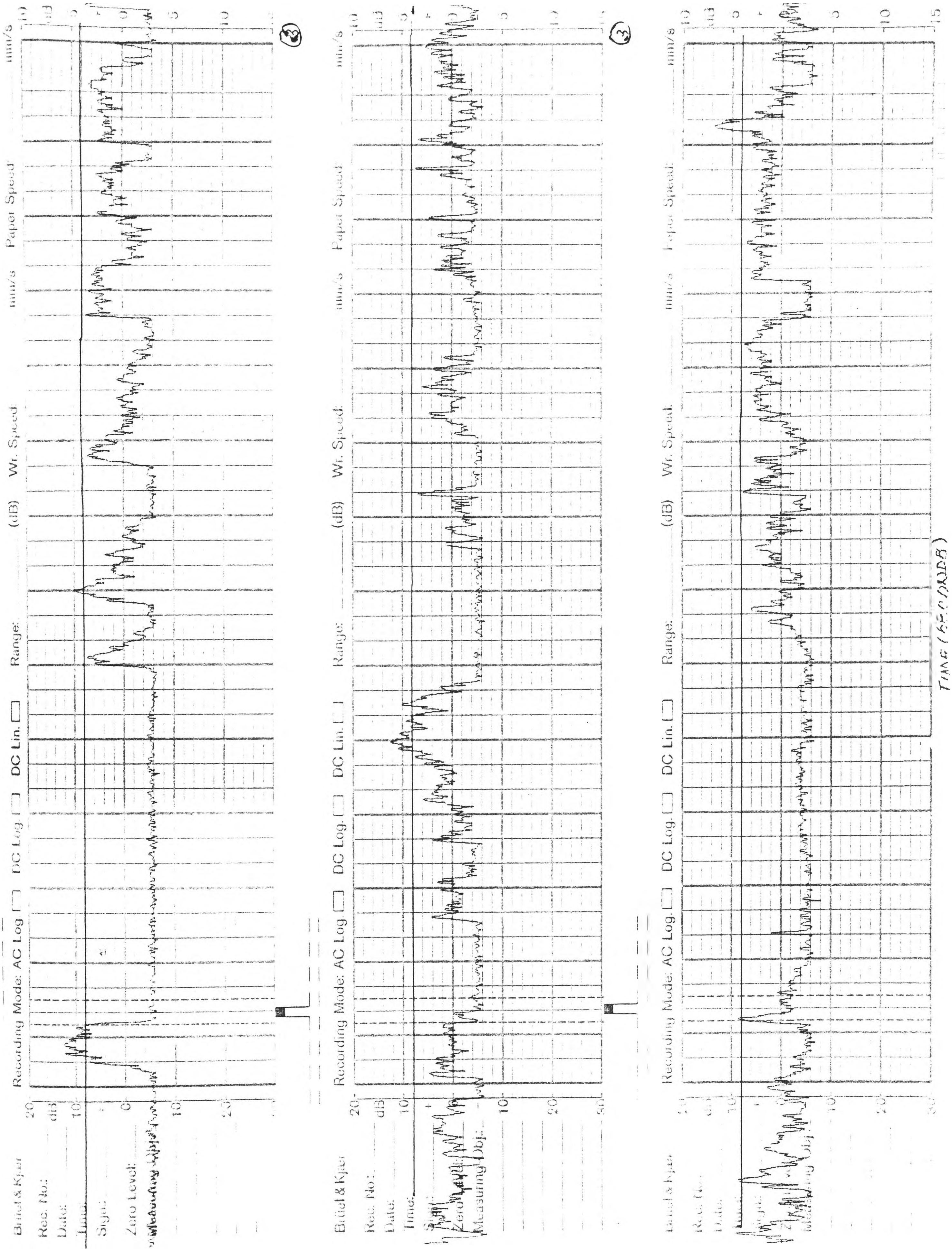

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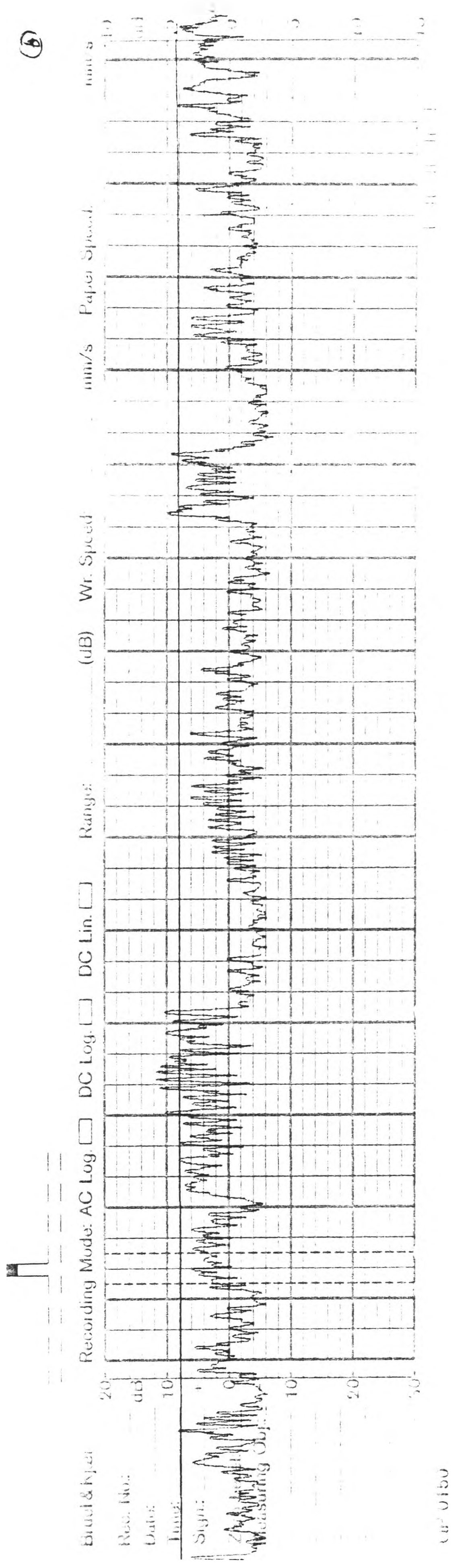

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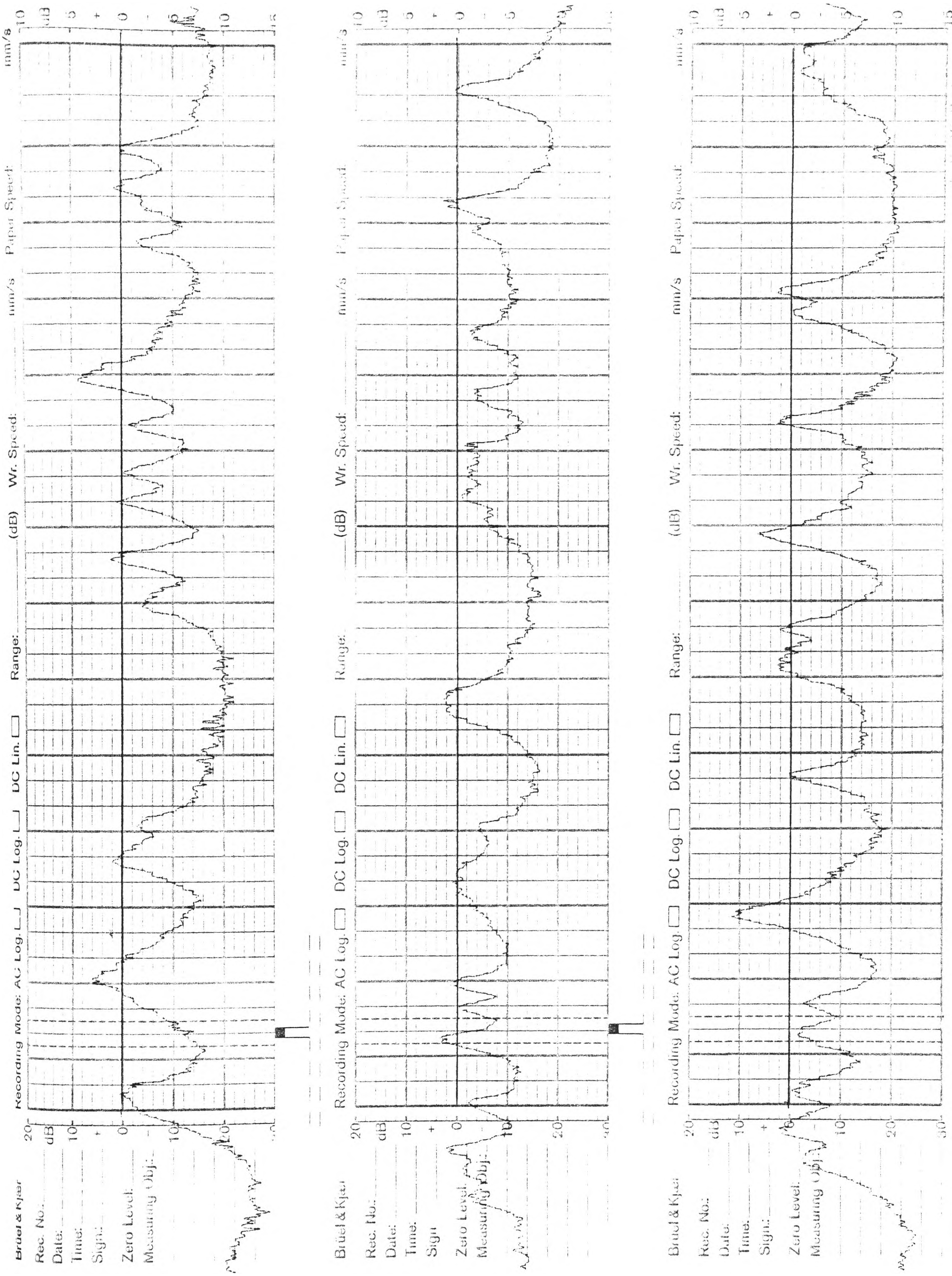

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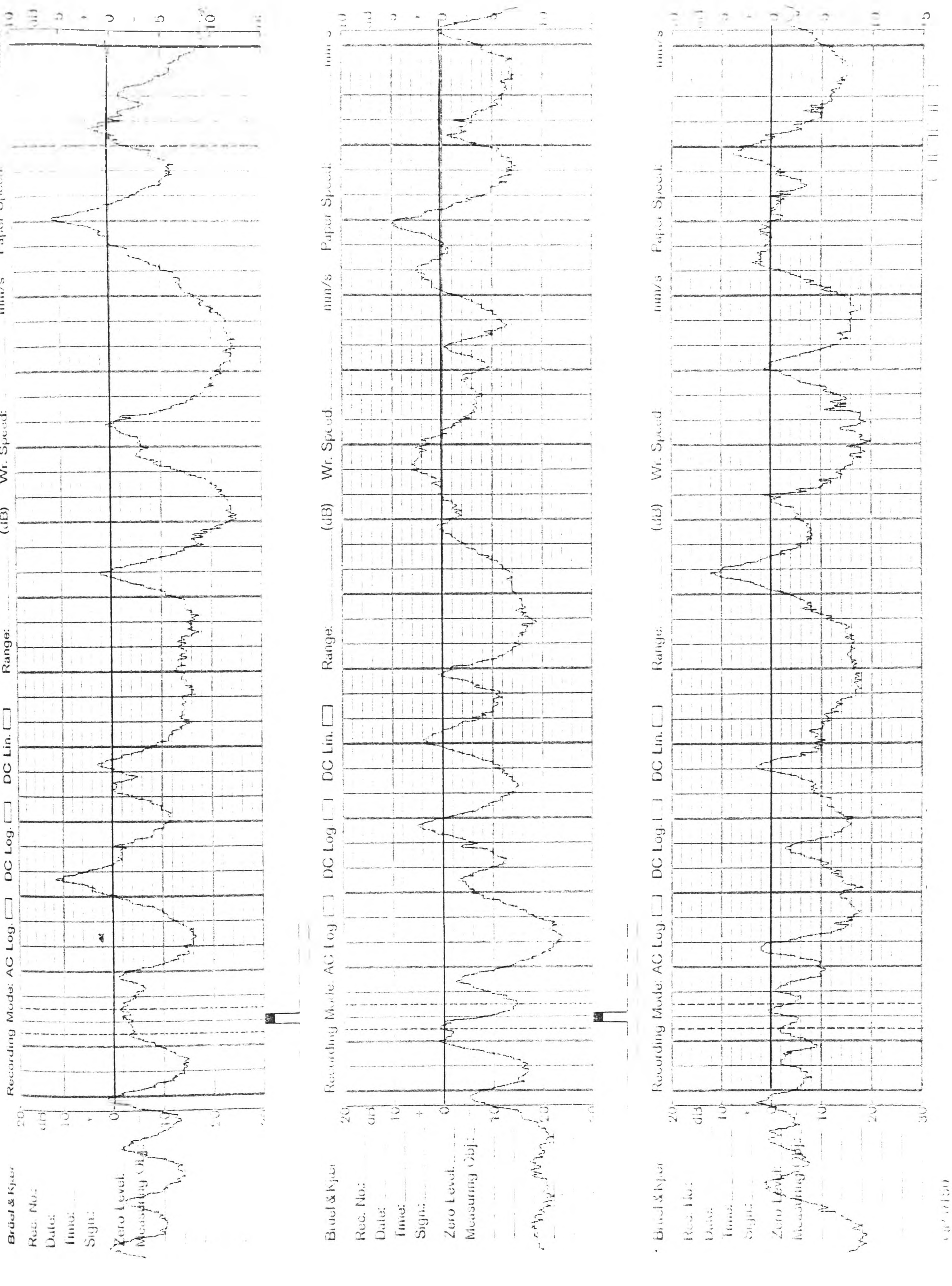

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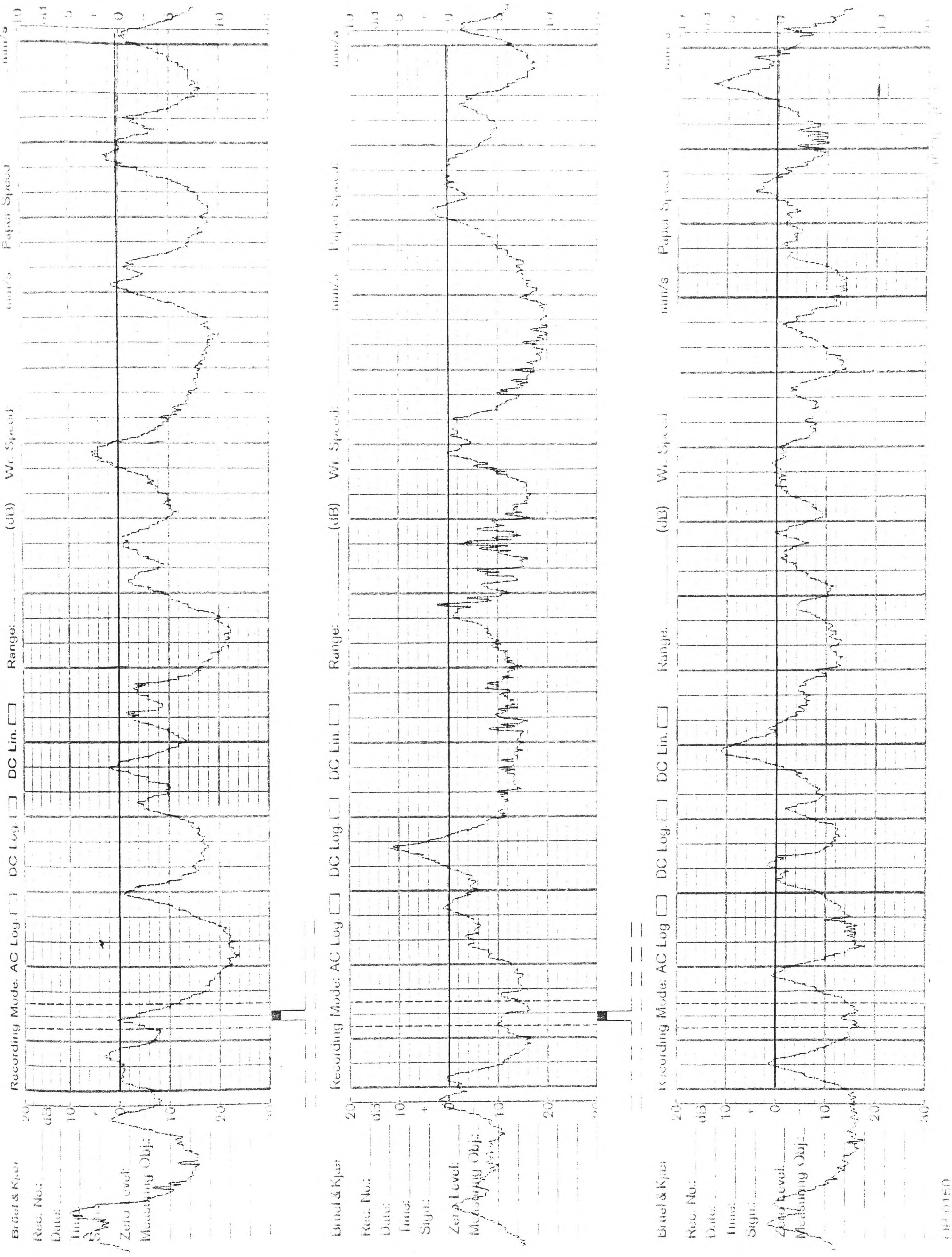

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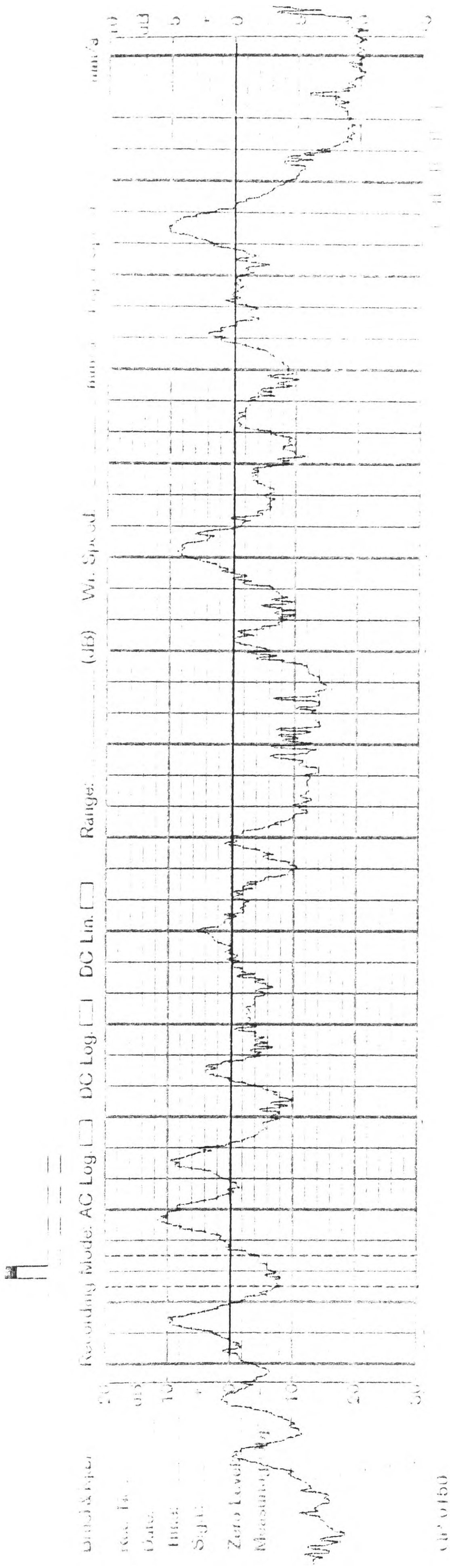

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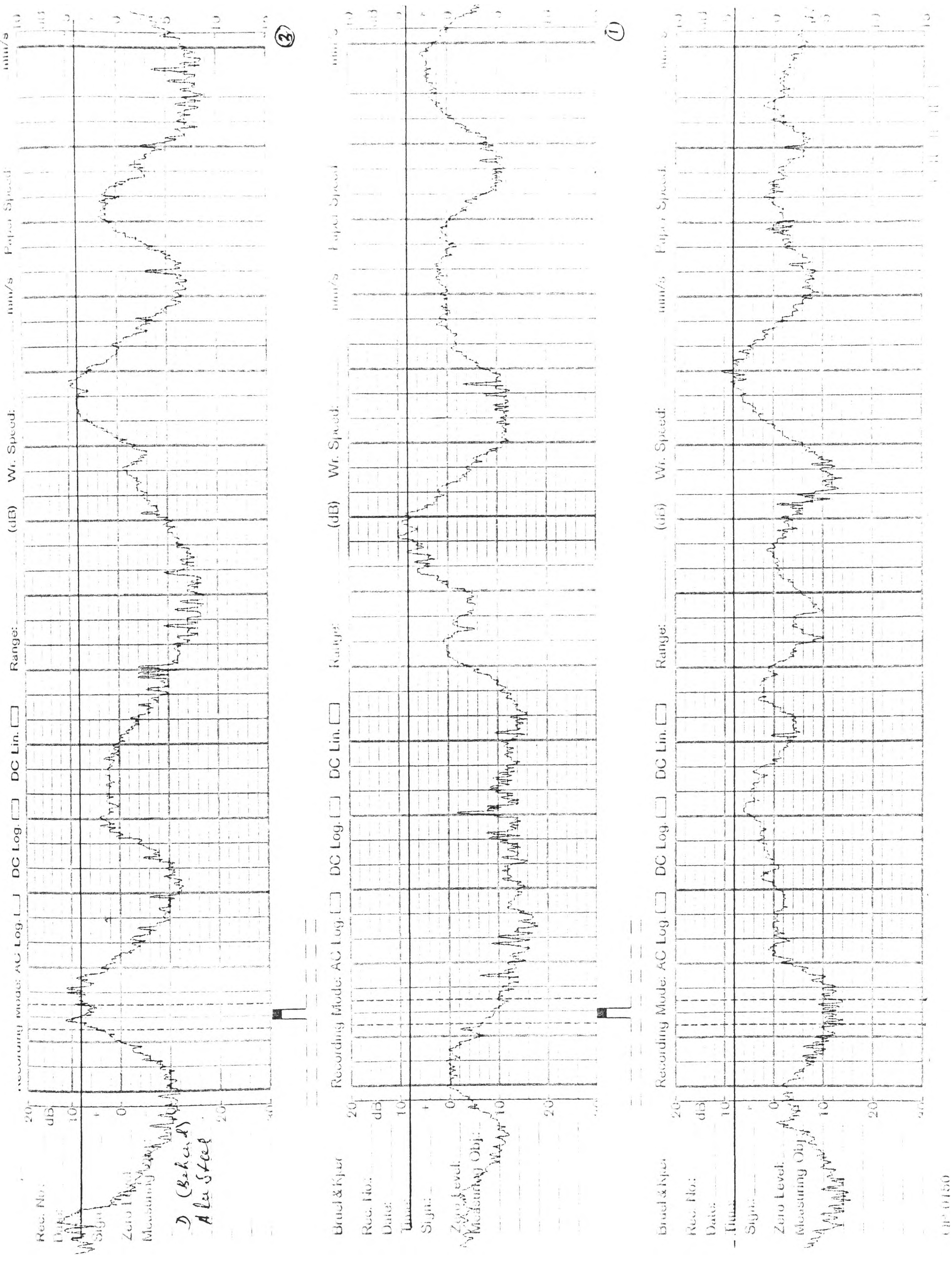

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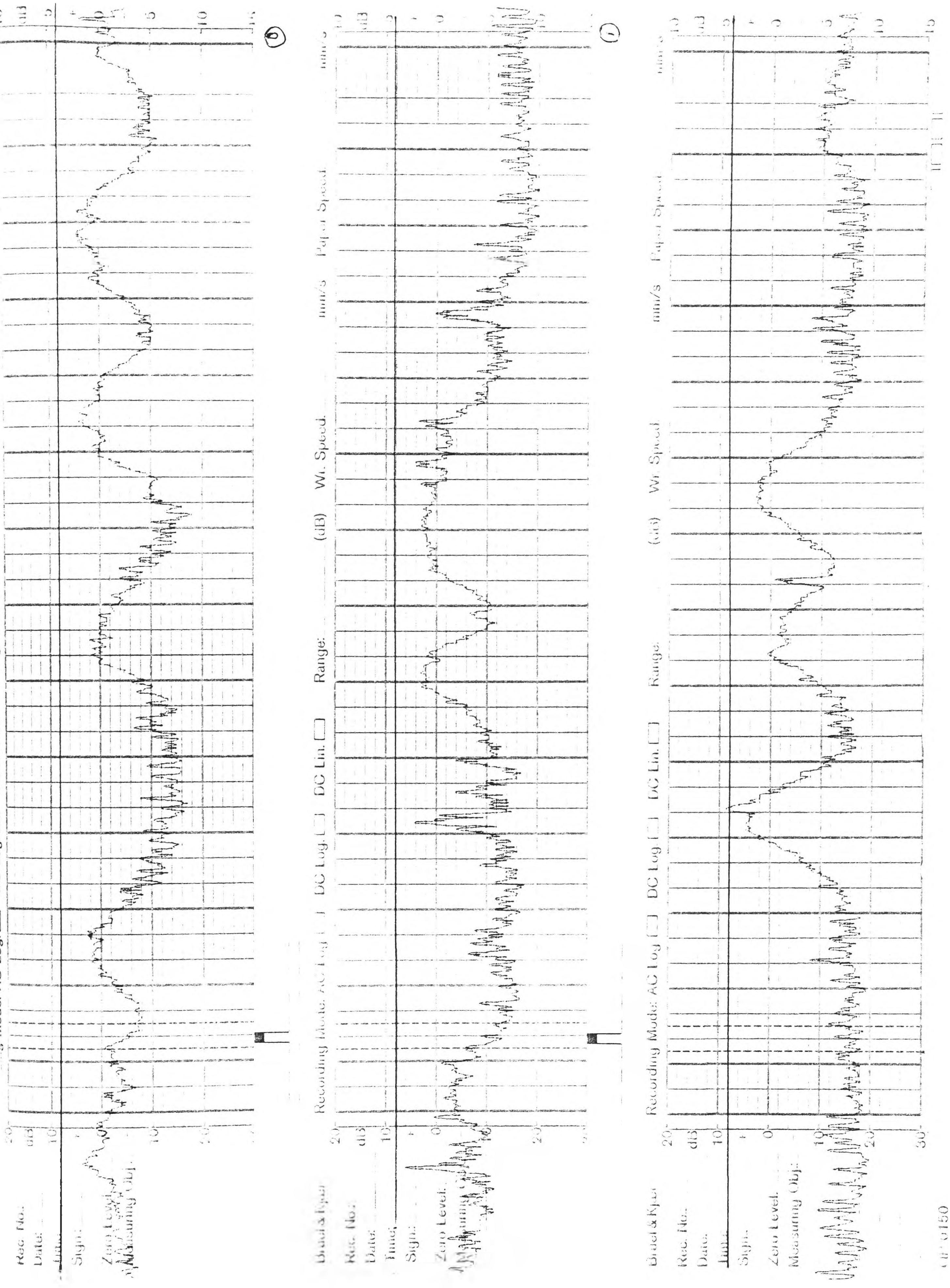

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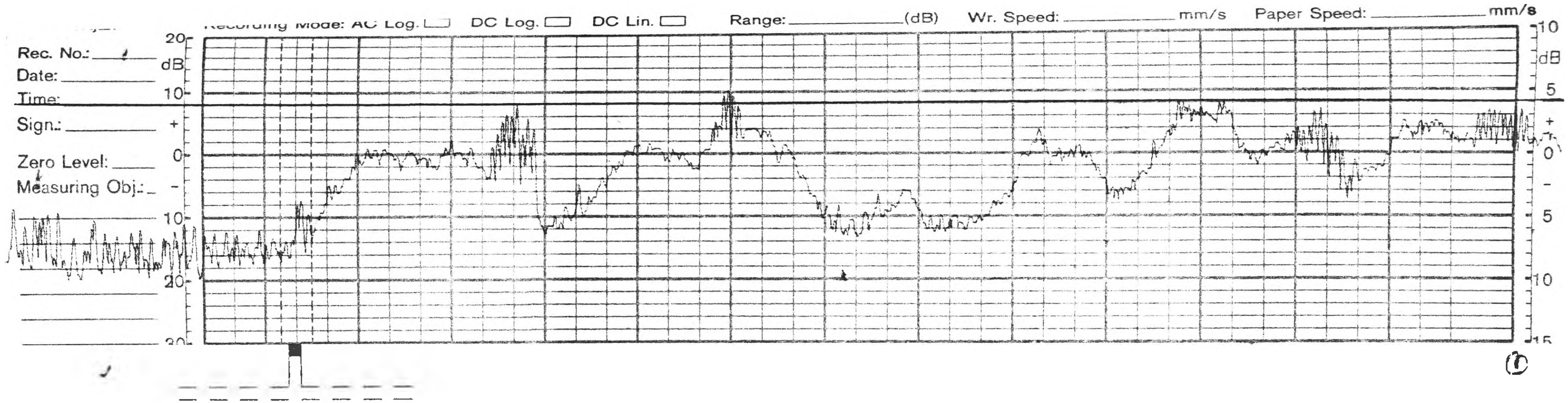
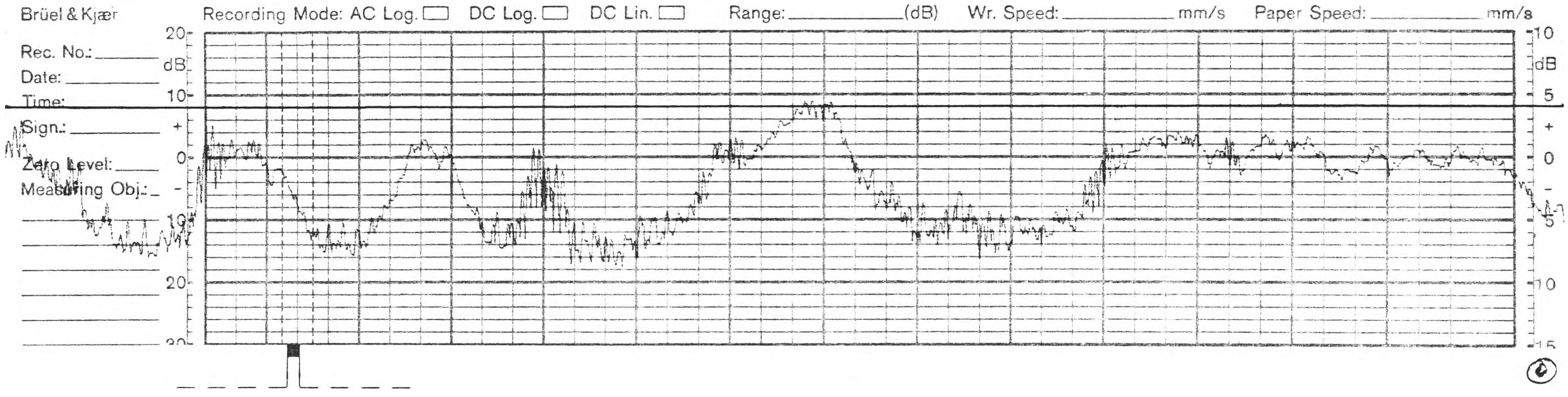
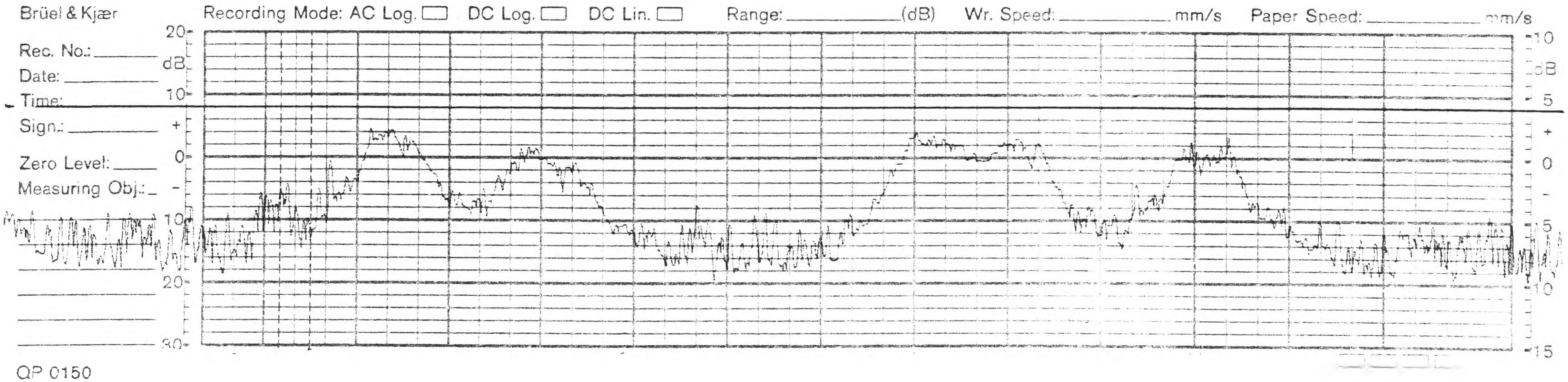
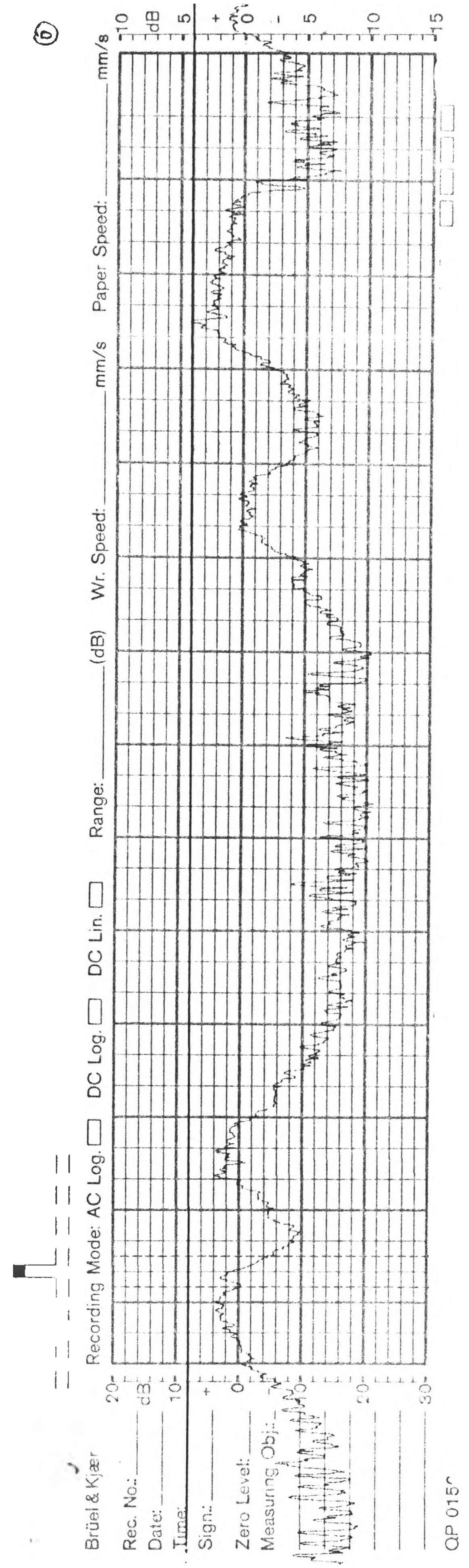
Contd: Test results of Type "D" barrier (with)









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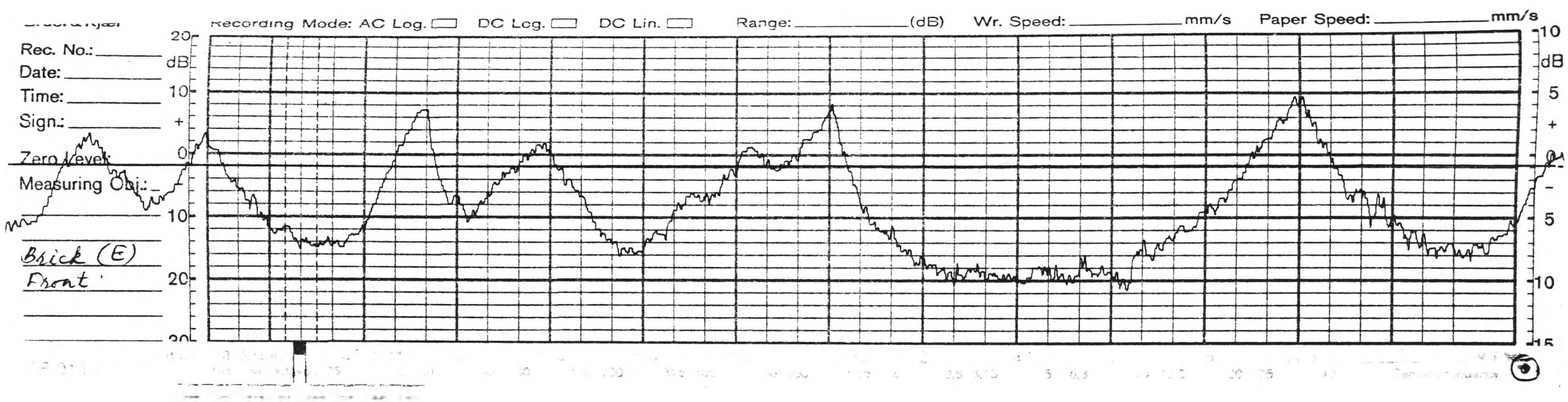
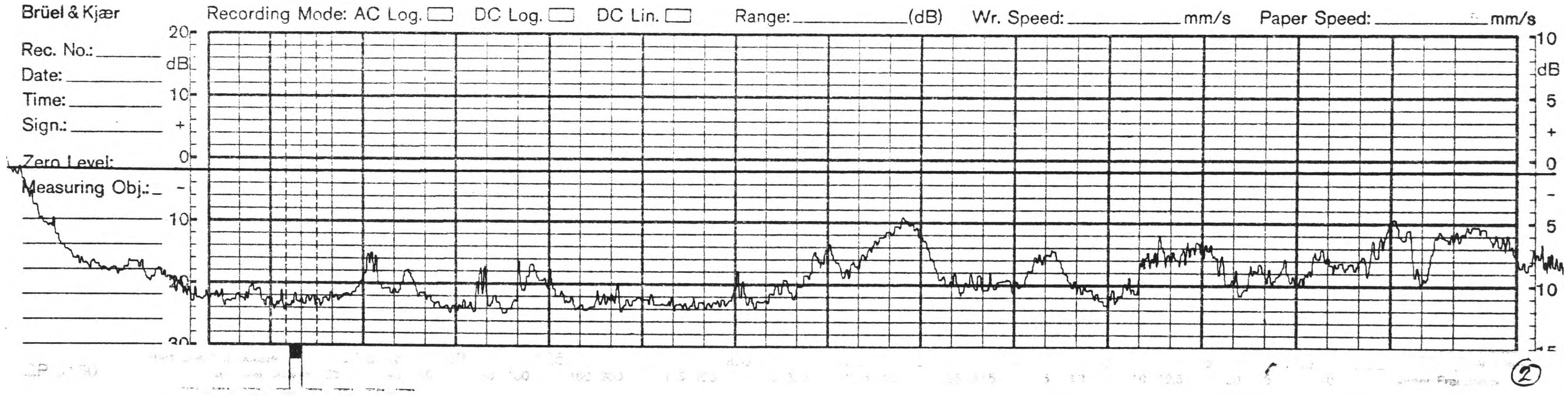
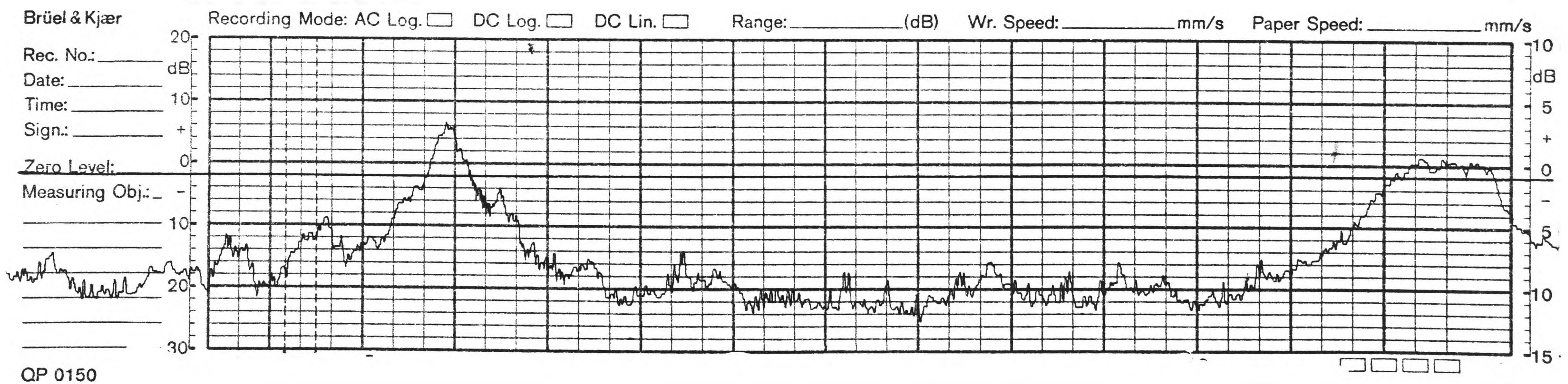
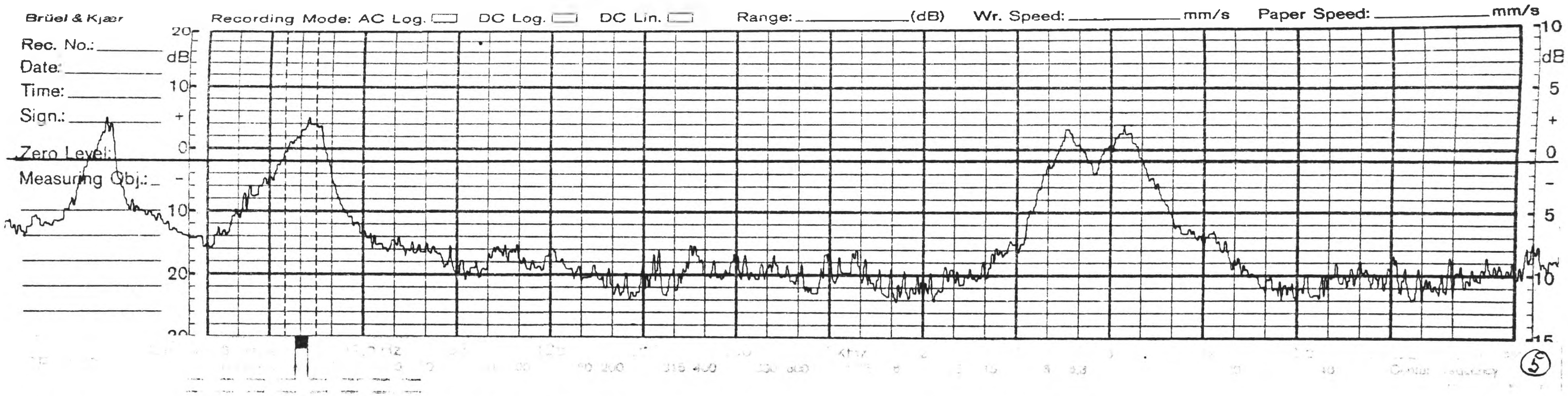
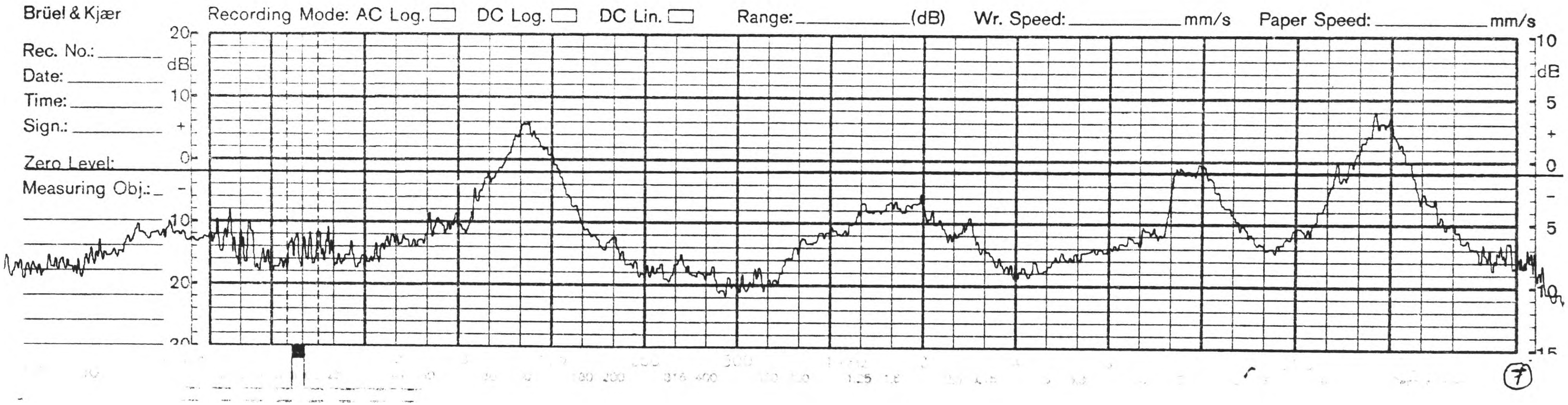


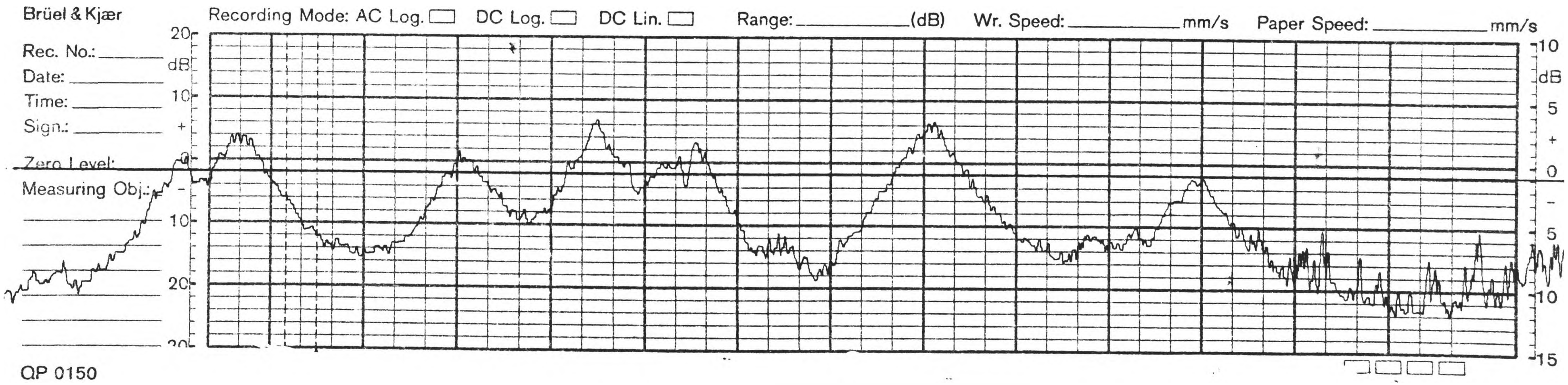




Test results of Type "E" barrier (witout)







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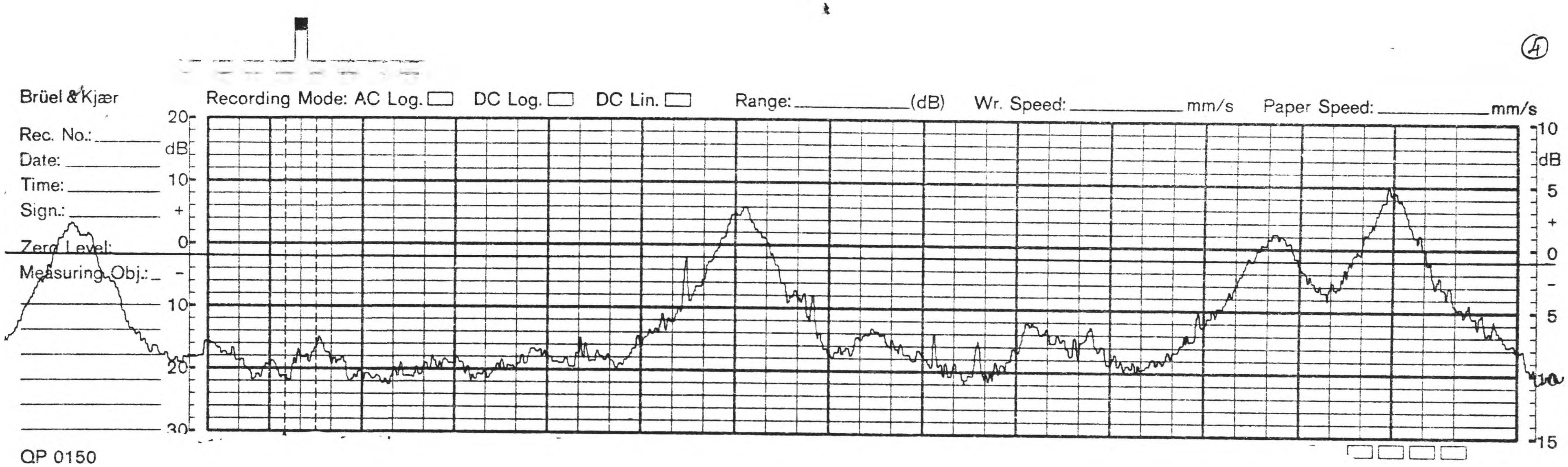
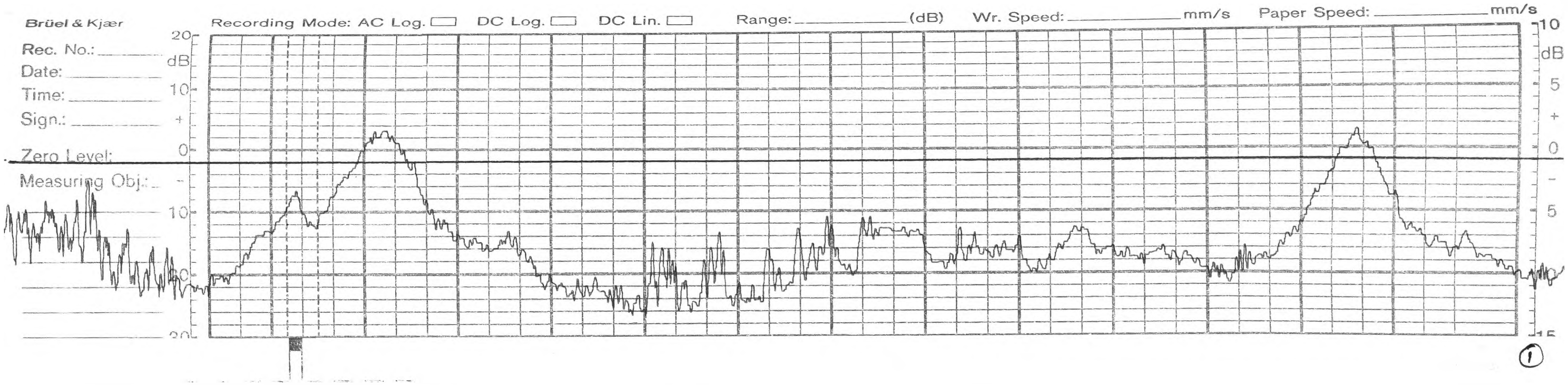
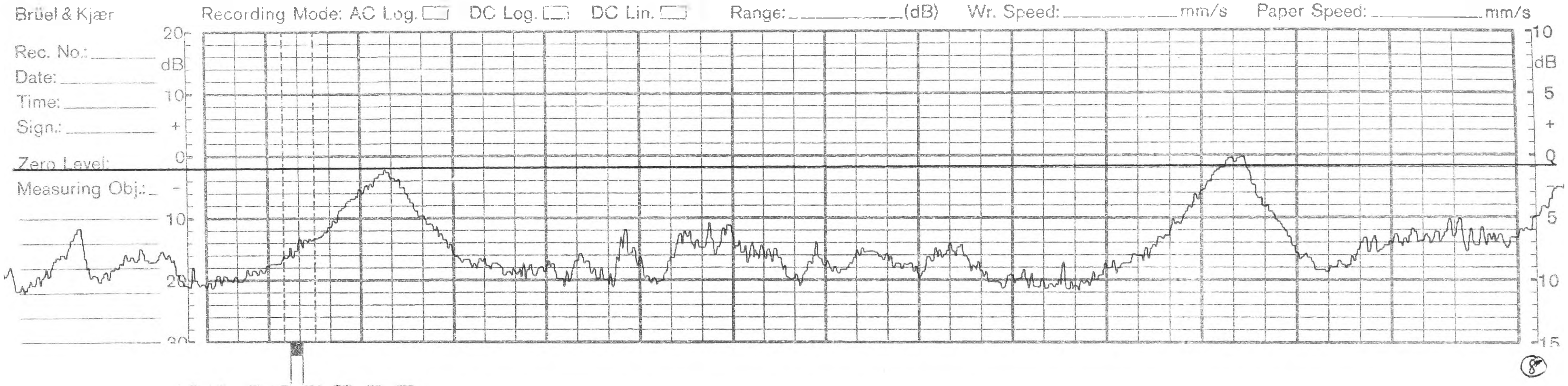
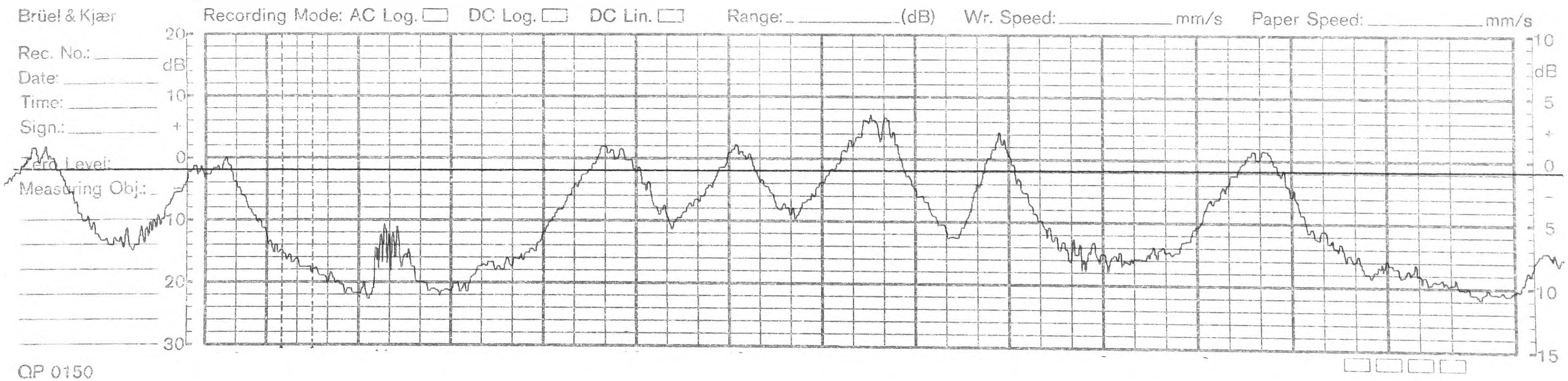


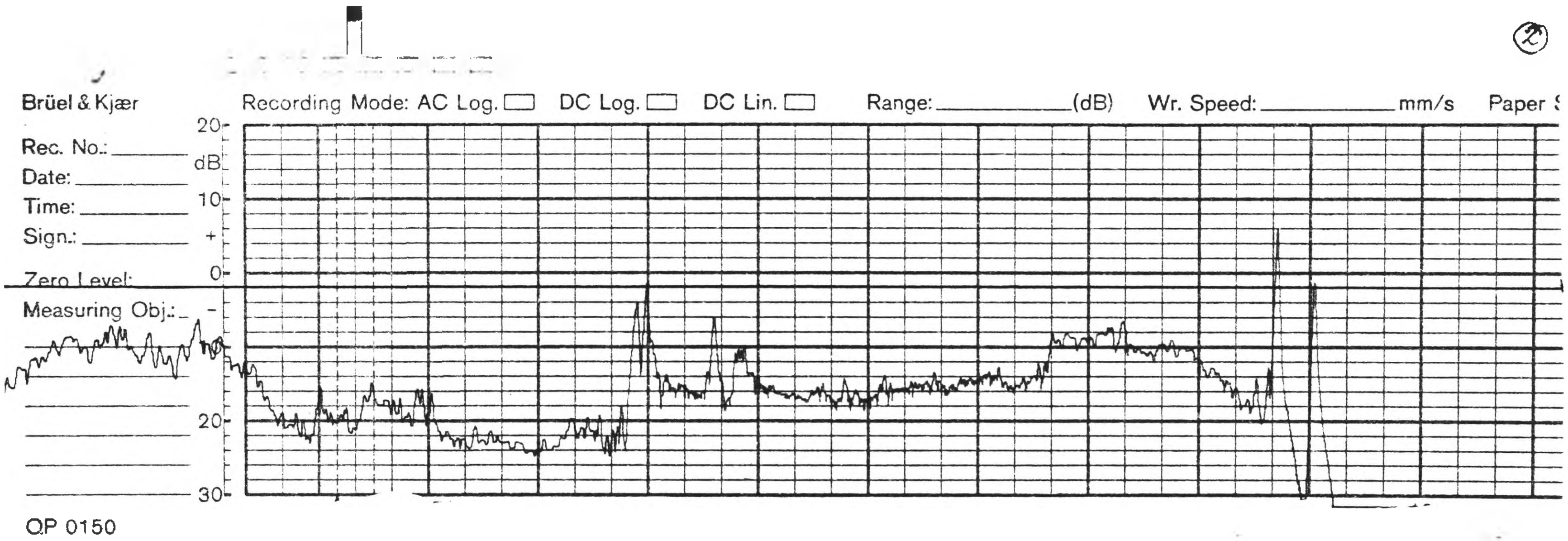
Contd: Test results of Type "E" barrier (without)

Contd: Test results of Type "E" barrier (without)

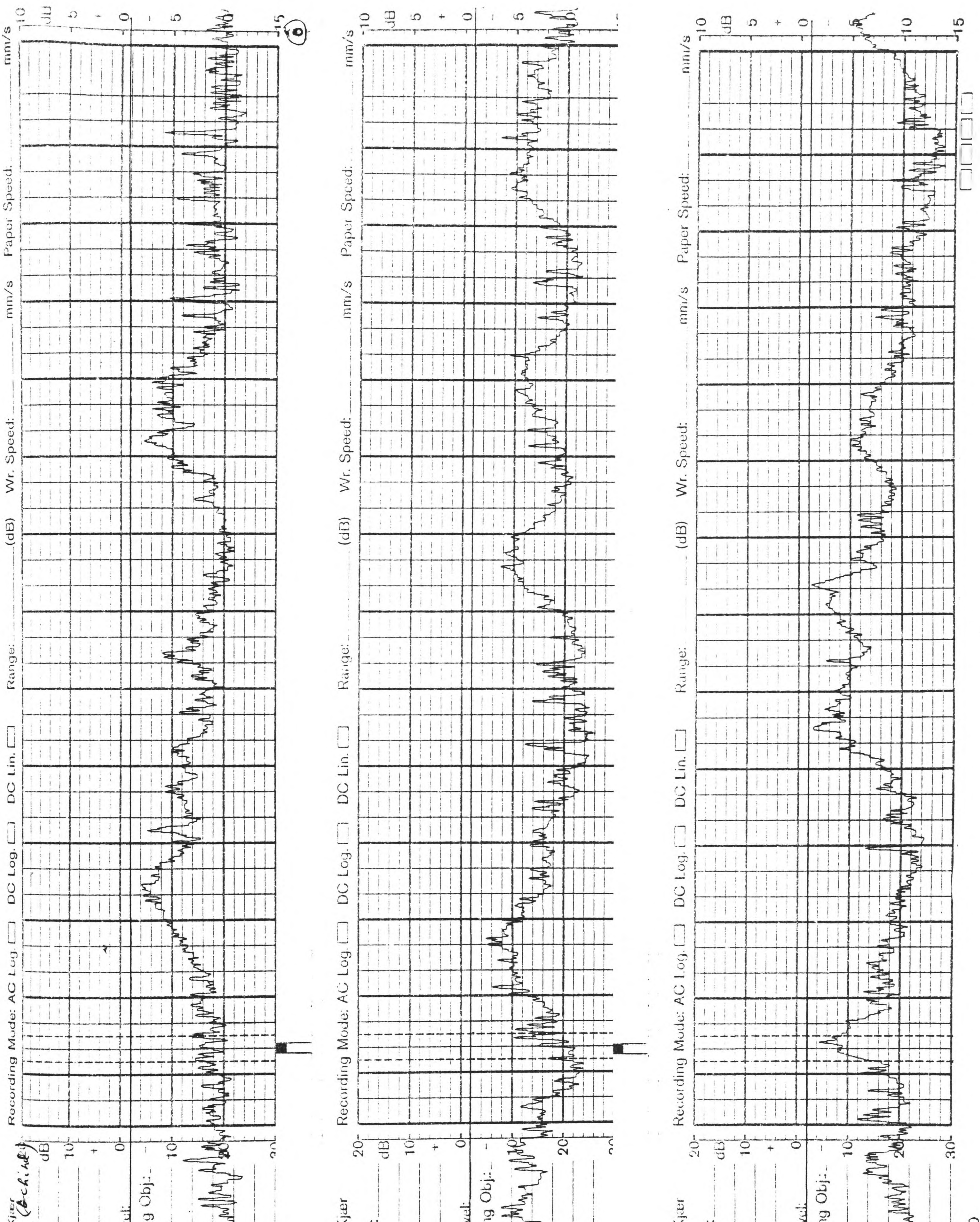






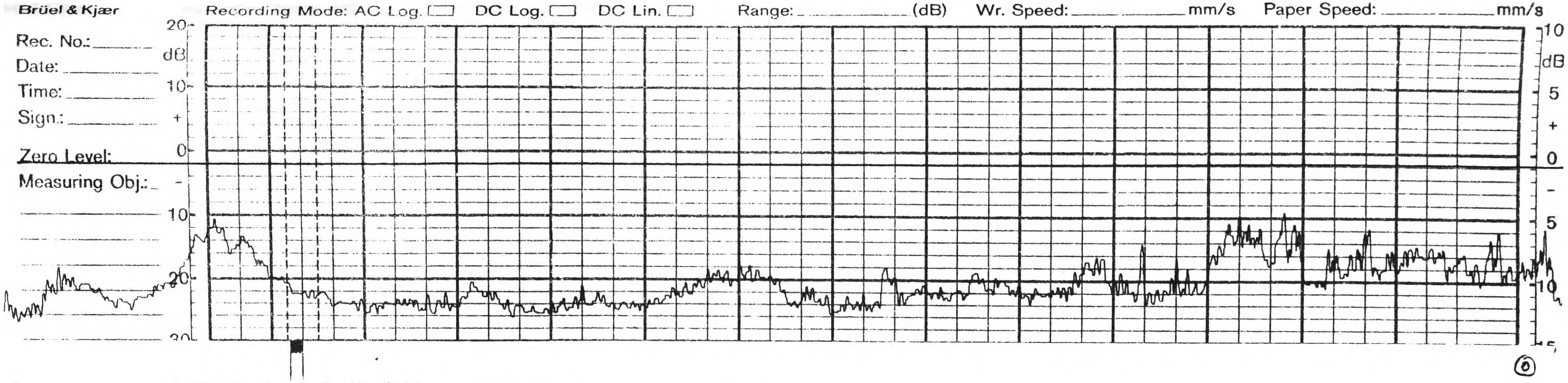


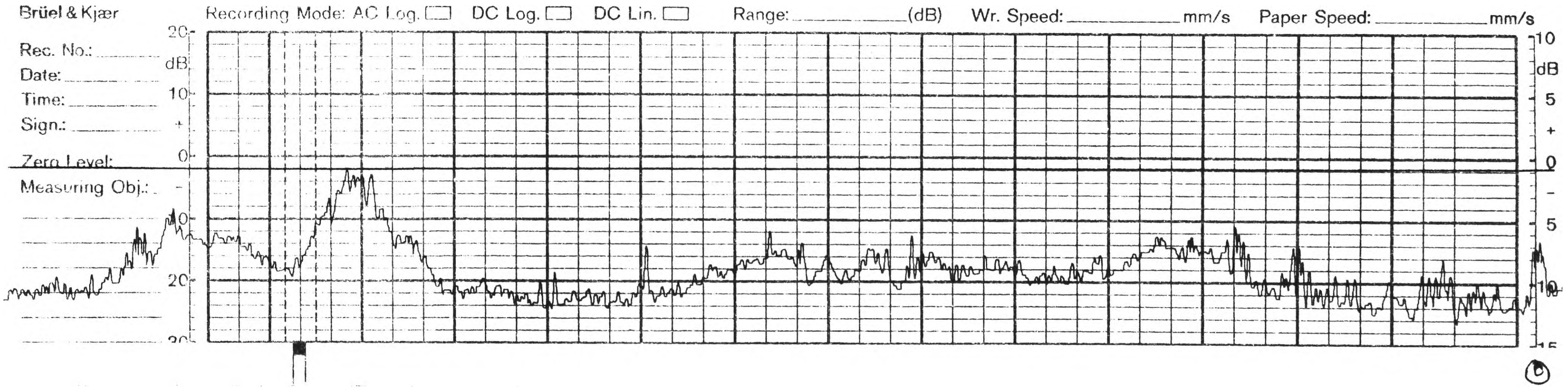
Test results of Type "E" barrier (with)

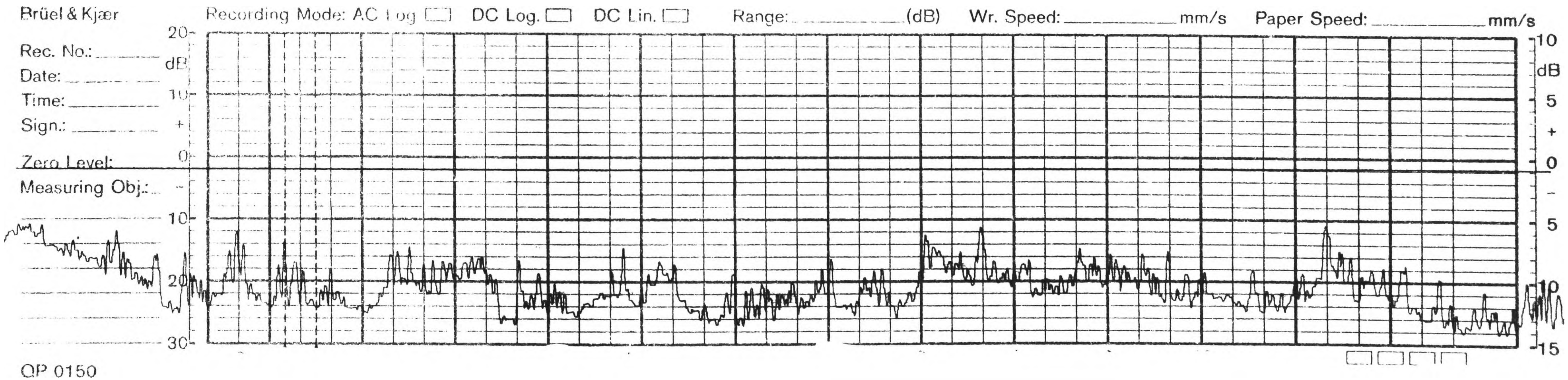


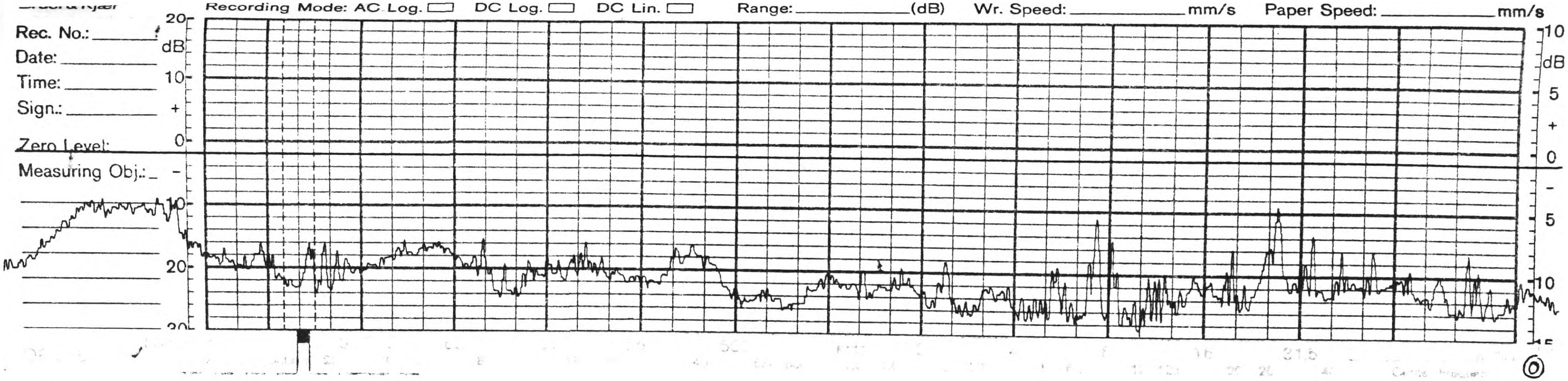
Contd: Test results of Type “E” barrier (with)

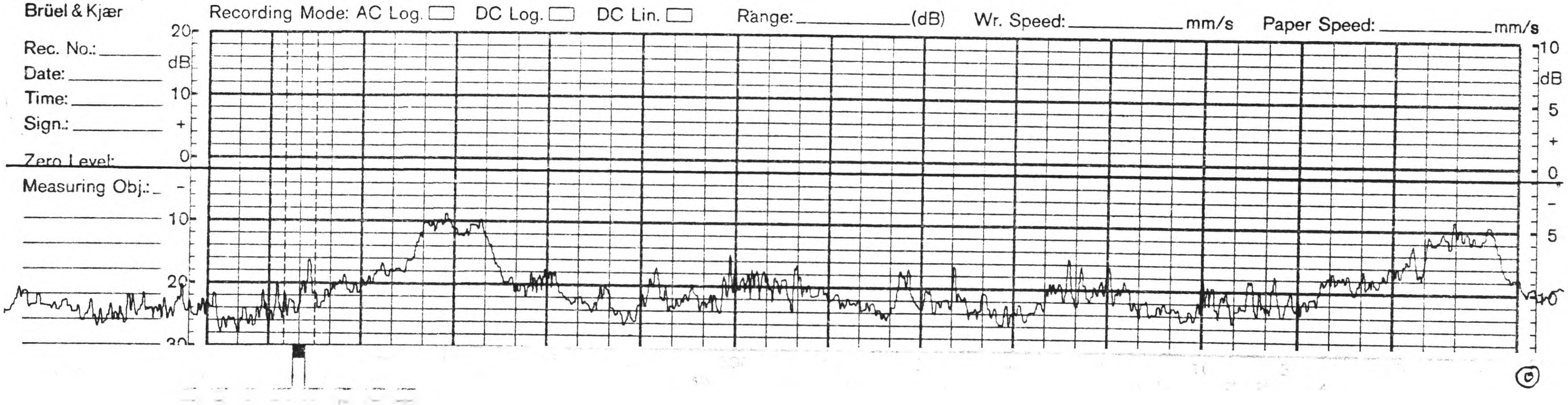
Contd: Test results of Type "E" barrier (with)

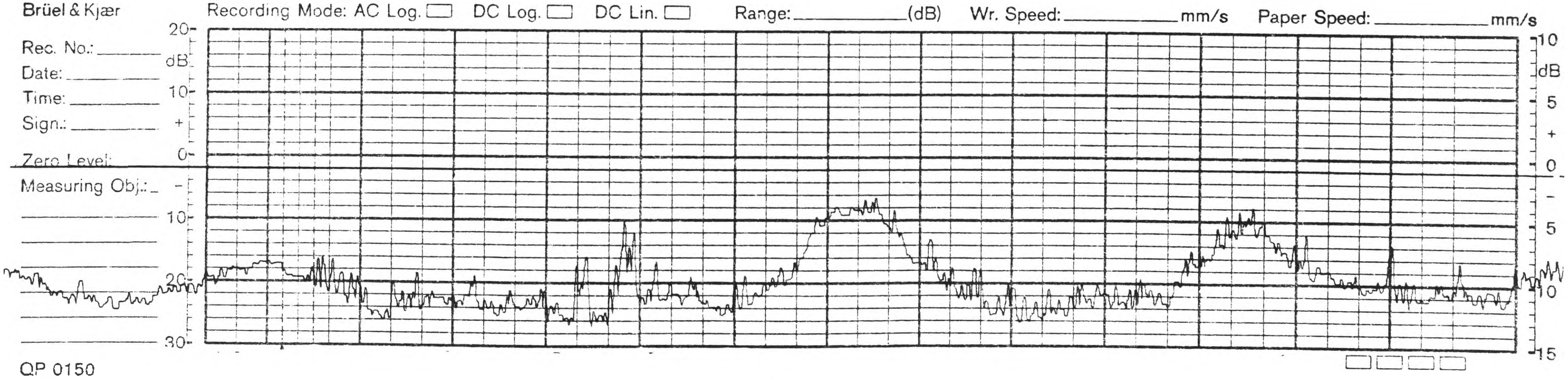












Contd: Test results of Type "E" barrier (with)

Field experiments at barrier site E (front of barrier)

Field experiments at barrier site E (behind the barrier)

APPENDIX 2

Flinders Street	06.00-24.00	31-Oct-91	Site 1	
Observation	Flow	Mean Speed	% H.V.	Noise level
1	608	90.5	8.5	76.5
2	634	80.4	9.8	74.9
3	772	75.3	14.1	82.3
4	1192	70	15.3	84.2
5	1091	88	11.4	87.4
6	1110	90.2	15.9	90.7
7	1174	78.7	14.6	88.3
8	1070	80.2	12.6	79.6
9	1358	82.5	12.9	86.4
10	1501	84.2	15	88.9
11	1481	79.5	9.5	79.9
12	1346	78	7.3	80.1
13	830	89	5	69.7
14	673	78.5	3.9	68.8
15	537	76.4	13.5	81.2
16	401	81.5	16.4	89.3
17	438	83.2	15.2	91.3
18	326	75.4	13.9	84.6

Regression Output		Site 1	
Constant		40.538638399	
Std Err of Y Est		2.8461557633	
R squared		0.8545943152	
No. of Observations		18	
Degrees of Freedom		14	
	Flow	Speed	% H.V.
X Coefficients	0.0029279978	0.2386206464	1.6630609622
Std Err of Coef.	0.0017931108	0.1255575347	0.1860505743
t-statistic	1.6329152095	1.9004884649	8.9387574756

Drive - by noise level survey data (Site 1)

Mt Ousley Road		06.00-24.00	24-Oct-91	Site 2
Observation	Flow	Mean Speed	% H.V.	Noise Level
1	140	80.5	6.8	61.3
2	614	79.8	8.8	69.7
3	936	86.4	3.9	62.9
4	1435	89.5	14.3	90.5
5	1197	70.2	4.9	60.6
6	1158	75.3	8.8	71.2
7	1193	90.4	13.6	89.3
8	1343	87.9	14.2	92.2
9	1190	82.4	12.5	87.8
10	1314	75.1	11	80.4
11	1277	76.3	10.7	80.6
12	1405	91.5	14.3	88.7
13	1249	84.3	12.6	87.4
14	811	89.2	13.4	90.1
15	776	87.6	9.8	85.3
16	574	86.5	2.3	63.6
17	489	79.4	2.5	60.3
18	577	80.6	1.6	62.5

Regression Output		Site 2	
Constant		14.43710854	
Std Err of Y Est		3.6419083765	
R squared		0.9302193474	
No. of Observations		18	
Degrees of Freedom		14	
	Flow	Speed	% H.V.
X Coefficients	0.004777144	0.4667018394	2.0683064897
Std Err of Coef.	0.0033150411	0.1672185859	0.3083984259
t-statistic	1.4410512146	2.7909687003	6.7066052103

Drive - by noise level survey data (Site 2)

Spring Hill Road		06.00-24.00	29-Oct-91	Site 3
Observation	Flow	Mean Speed	% H.V.	Noise Level
1	767	76.3	5.6	59.8
2	1141	78.6	4	60.3
3	1515	77.5	7.1	61.2
4	1150	92.4	8.6	84.5
5	1178	86.3	11.5	81.4
6	1205	93	10.9	88.7
7	1269	84.5	8.4	85.6
8	1231	80.1	7.9	82.2
9	1327	76.4	13.4	81.6
10	1711	73.9	11.5	80
11	1566	72	10.3	69.9
12	1477	88.5	12.7	85.3
13	1013	86	10.8	87.1
14	875	79.7	14.2	83.9
15	722	72.3	7.3	74.1
16	594	90.2	6.5	73.2
17	455	94.3	2.3	68.5
18	276	80.5	0.8	60.4

Regression Output		Site 3	
Constant		7.6581948236	
Std Err of Y Est		5.4613473874	
R squared		0.7665918128	
No. of Observations		18	
Degrees of Freedom		14	
	Flow	Speed	% H.V.
X Coefficients	-0.001377066	0.6152846702	2.2399687403
Std Err of Coef.	0.0045428804	0.1912101292	0.4631101547
t-statistic	-0.303126108	3.2178455865	4.8367946973

Drive - by noise level survey data (Site 3)

North Fields Avenue		06.00-24.00	21-Oct-91	Site 4
Observation	Flow	Mean Speed	% H.V.	Noise Level
1	745	60.4	8.1	64.2
2	1124	79.8	7.9	66.7
3	1497	68.9	3.6	65.8
4	1112	80.5	14.5	79.8
5	990	85.1	16.8	70.3
6	1108	89.7	13.9	88.4
7	1028	70.3	8.1	74.7
8	1214	75.6	7.9	75.1
9	1555	84.5	12.5	89.2
10	1510	78.7	10.6	76.4
11	1398	78.1	11.5	79.7
12	834	90.2	9.4	86.5
13	658	75.2	10.7	78.2
14	518	67.2	8.6	69.4
15	392	78.7	4.9	67.3
16	273	86.4	0.2	65
17	54	80.6	0.3	62.2
18	18	84.5	0.1	58.4

Regression Output		Site 4	
Constant		29.039582534	
Std Err of Y Est		5.7733318292	
R squared		0.6745404327	
No. of Observations		18	
Degrees of Freedom		14	
	Flow	Speed	% H.V.
X Coefficients	0.0063677853	0.3963559613	1.6630609622
Std Err of Coef.	0.0037986076	0.1782987677	0.3763682753
t-statistic	1.6763472095	2.222987665	2.3336432268

Drive - by noise level survey data (Site 4)

Crown Street	06.00-24.00	18-Oct-91	Site 5	
Observation	Flow	Mean Speeds	% H.V.	Noise Level
1	118	59.9	8.7	60.6
2	227	67.4	2.8	61.4
3	535	76.3	13.7	74.3
4	912	85.9	8.9	75.1
5	943	86.5	3.7	72.6
6	1036	90.3	12.5	80.9
7	1080	84.7	10.3	82.8
8	1042	88.1	10.1	85.3
9	1053	75.5	12.4	88.7
10	1065	87.6	9.6	86.4
11	1136	92.1	14.3	89.1
12	1148	89.4	11.9	87.2
13	1046	86.3	10.2	80.8
14	622	88.2	8.1	79.4
15	544	80.7	4	68.5
16	436	76.3	1	60.1
17	330	70.5	0.2	59.3
18	116	80	0.4	58.4

Regression Output		Site 5	
Constant		44.675214761	
Std Err of Y Est		3.169249139	
R squared		0.9331944684	
No. of Observations		18	
Degrees of Freedom		14	
	Flow	Speed	% H.V.
X Coefficients	0.0170620126	0.1258309587	0.9374818723
Std Err of Coef.	0.0043630923	0.1473580735	0.2351045213
t-statistic	3.9105321481	0.853912892	3.9875110321

Drive - by survey data (Site 5)

Keira Street	06.00-24.00	12-Oct-91	Site 6	
Observation	Flow	Mean Speed	% H.V.	Noise Level
1	60	85.2	4.5	69.5
2	137	80.5	12.5	80.8
3	371	79.4	4.9	67.4
4	837	84.3	10.1	80.1
5	853	90.1	8	68.9
6	968	92.5	14.6	88.7
7	1075	87.6	7.5	73.4
8	1093	83.3	9.2	80.7
9	1040	80.2	11.3	84.5
10	1014	78.6	10.7	82.7
11	1097	77.9	13.5	88.9
12	1073	89.5	12	84.5
13	896	80.3	7.4	65.4
14	597	87.7	4	60.3
15	714	81	2.2	59.4
16	424	78.6	1.7	58.1
17	226	75.4	0.2	54.3
18	101	89	0	51.5

Regression Output		Site 6	
Constant		64.971558419	
Std Err of Y Est		3.2513170014	
R squared		0.9411466054	
No. of Observations		18	
Degrees of Freedom		14	
	Flow	Speed	% H.V.
X Coefficients	0.0014146099	-0.148525114	2.4927242155
Std Err of Coef.	0.002694229	0.1601674429	0.2219413074
t-statistic	0.5250518423	-0.927311511	11.231456844

Drive - by survey data (Site 6)

Burrelli Street	06.00-24.00	6-Nov-91	Site 7	
Observation	Flow	Mean Speed	% H.V.	Noise Level
1	40	66.4	2.9	59.3
2	126	79.8	6.3	74.1
3	365	60.5	8	72.5
4	785	89.3	4.9	68.9
5	867	90.1	10.4	85.6
6	944	79.1	12.6	86.3
7	939	92.4	8.7	80.1
8	921	86.7	11.6	84.8
9	862	88	10.3	87.6
10	877	81.4	9.5	79.3
11	996	88.8	6.8	81.4
12	897	83.2	13.1	85.7
13	726	79.1	10.5	79.2
14	410	78.8	7.4	78.3
15	443	86.4	5.1	77.6
16	313	80.9	2	69.9
17	239	88.6	0.9	66.5
18	97	87	0.1	59.8

Regression Output		Site 7	
Constant		36.495111583	
Std Err of Y Est		3.2599675311	
R squared		0.8864204746	
No. of Observations		18	
Degrees of Freedom		14	
	Flow	Speed	% H.V.
X Coefficient(s)	0.000128776	0.3111075	1.9536969
Std Err of Coef.	0.005243882	0.1354359	0.3994084
t-statistic	0.024556916	2.2970995	4.8914736

Drive - by survey data (Site 7)

Regression Output	Pooled Data
Constant	31.005797
Std Err of Y Est	4.5669879616
R squared	0.8244744397
No. of Observations	126
Degrees of Freedom	116

	Flow	Speed	% H.V.	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
X coefficients	0.0029279978	0.2386206464	1.6630609622	-2.705592335	-4.336419963	-4.178277254	-4.570047705	-2.607795808	-5.2441946
Std Err of Coef	0.0017931108	0.1255575347	0.1860505743	1.597492018	1.576578107	1.622119633	1.581600360	1.532845078	1.5270075
t-statistic	1.6329152095	1.9004884649	8.9387574756	-1.69364998	-2750526562	-2.57581325	-2.88950851	-1.70127813	-3.4344423

Results of the Regression Analysis for the pooled data of drive -by noise survey

Regression Output		Pooled Data	
Constant		27.41903	
Std Err of Y Est		4.739922	
R squared		0.80115	
No. of Observations		126	
Degrees of Freedom		122	
	Flow	Speed	% H.V.
X Coefficient(s)	0.002056	0.381303	1.809708
t-statistic	1.641373	6.3446637	15.64014

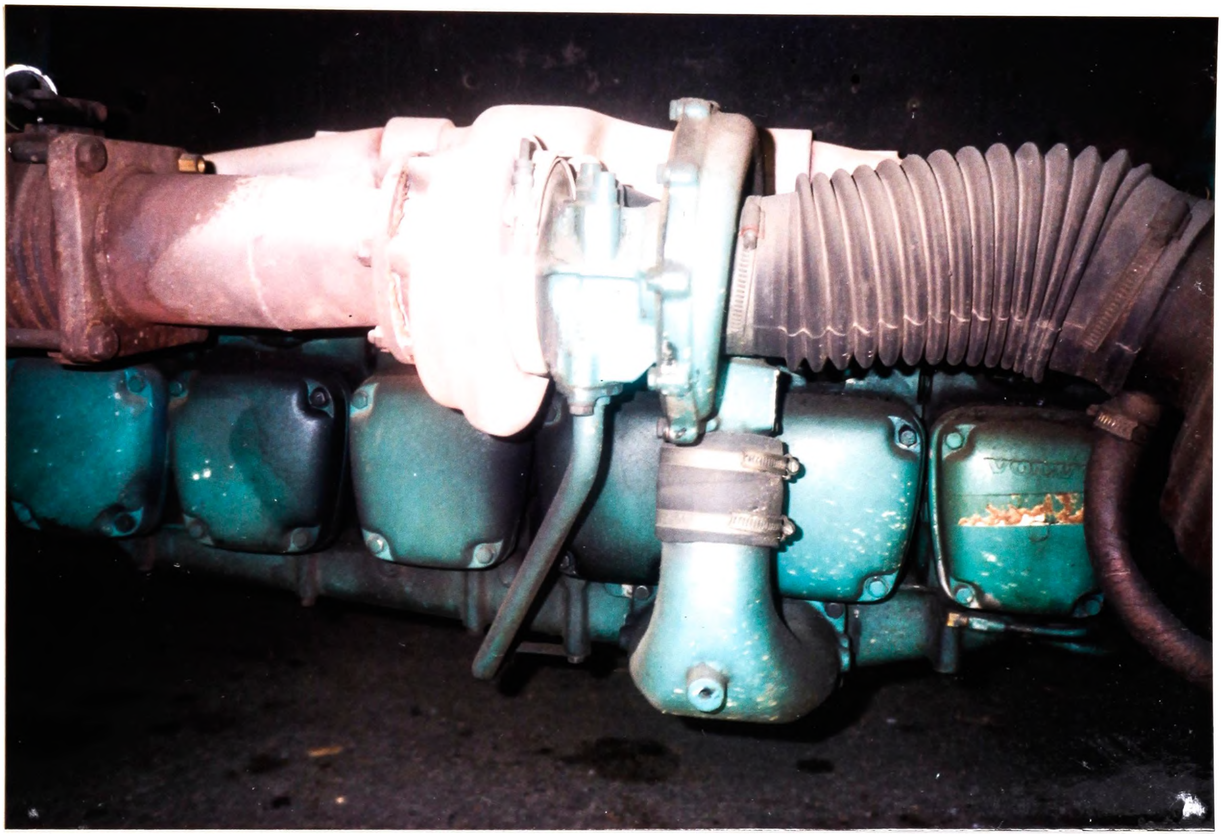
Regression analysis for a general traffic noise model

### Princess Highway(Flinders Street).###			
### 31 OCT.1991 ###			
TrafiCOMP III by StreeterAmet			
Volume by Lane Report			
with Column and Hourly and 24 Hour Totals			
			Page # 1
File * 01			
Station 1			
Identification 1			
Interval 15 minutes			
Ratio 2.00			
Start date 31 OCT 91			Start time 06:00
Stop date 31 OCT 91			Stop time 24:00
31-Oct-91			
06:15	74	82	156
06:30	139	67	206
06:45	96	53	149
07:00	46	51	97
Total *****	355	253	608
07:15	93	65	158
07:30	59	44	103
07:45	146	81	227
08:00	113	33	146
Total *****	411	223	634
08:15	70	109	179
08:30	59	148	207
08:45	104	79	183
9:00		88	203
Total *****	348	424	772
09:15	137	114	251
09:30	126	252	378
09:45	253	79	332
10:00	159	72	231
Total *****	675	517	1192
10:15	145	104	249
10:30	98	171	269
10:45	169	114	283
11:00	153	137	290
Total *****	565	526	1091
11:15	72	179	251
11:30	156	143	299

11:15	72	179	251			
11:30	156	143	299			
11:45	125	157	282			
12:00	131	147	278			
Total *****	484	626	1110			
12:15	111	165	276			
12:30	127	152	279			
12:45	132	159	291			
13:00	138	190	328			
Total *****	508	666	1174			
13:15	139	152	291			
13:30	155	134	289			
13:45	139	104	243			
14:00	147	100	247			
Total *****	580	490	1070			
14:15	143	142	285			
14:30	190	133	323			
14:45	214	177	391			
15:00	161	198	359			
Total *****	708	650	1358			
15:15	271	99	370			
15:30	216	82	298			
15:45	172	235	407			
16:00	212	214	426			
Total *****	871	630	1501			
16:15	163	157	320			
16:30	162	187	349			
16:45	213	188	401			
17:00	181	230	411			
Total *****	719	762	1481			
17:15	172	224	396			
17:30	150	194	344			
17:45	202	139	341			
18:00	173	92	265			
Total *****	697	649	1346			
18:15	207	63	270			
18:30	116	35	151			
18:45	147	89	236			
19:00	111	62	173			
Total *****	581	249	830			
19:15	76	93	169			
19:30	67	85	152			
19:45	90	90	180			

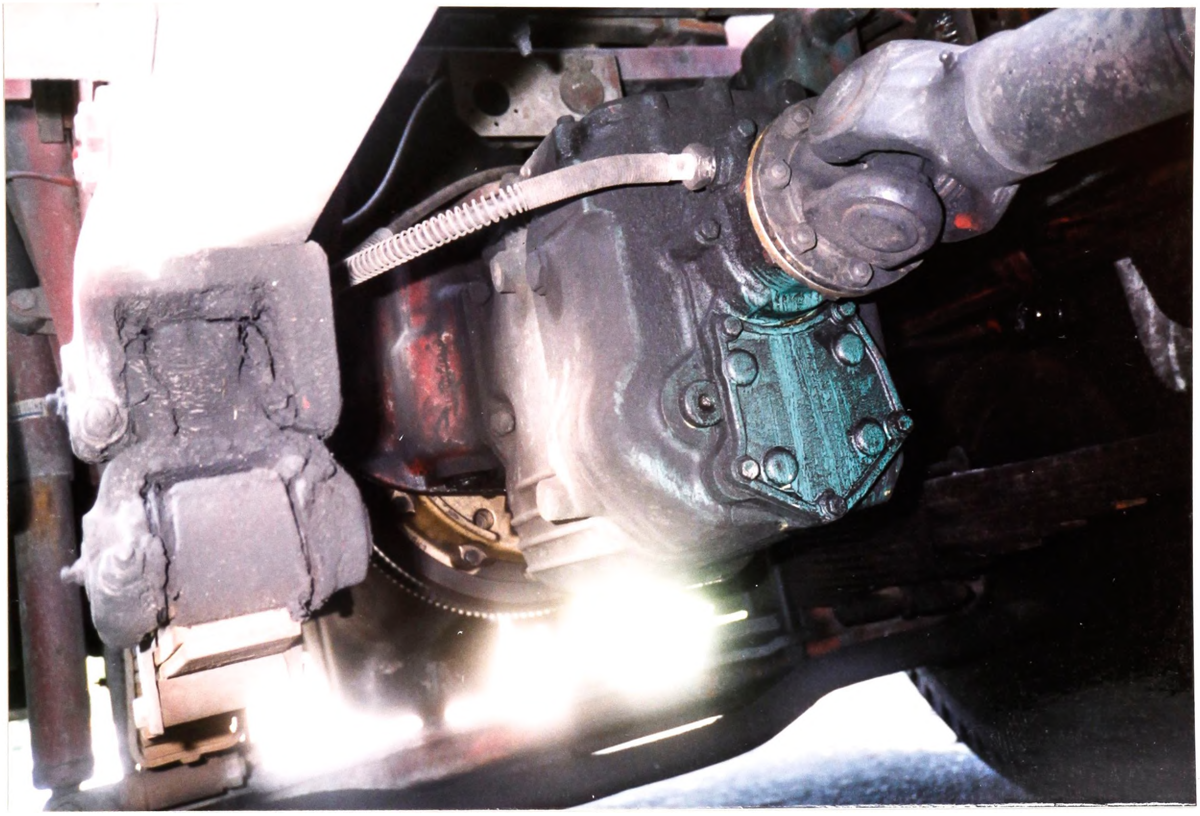
20:00	77	95	172		
Total *****	310	363	673		
20:15	50	73	123		
20:30	81	85	166		
20:45	69	78	147		
21:00	47	54	101		
Total *****	247	290	537		
21:15	73	64	137		
21:30	47	61	108		
21:45	25	48	73		
22:00	36	47	83		
Total *****	181	220	401		
22:15	49	91	140		
22:30	29	75	104		
22:45	52	43	95		
23:00	41	58	99		
Total *****	171	267	438		
23:15	56	37	93		
23:30	31	30	61		
23:45	65	21	86		
24:00	59	27	86		
Total *****	211	115	326		
- -					
31-Oct-91					
18 Hour					
Total *****		8622	7920	16542	

APPENDIX 3

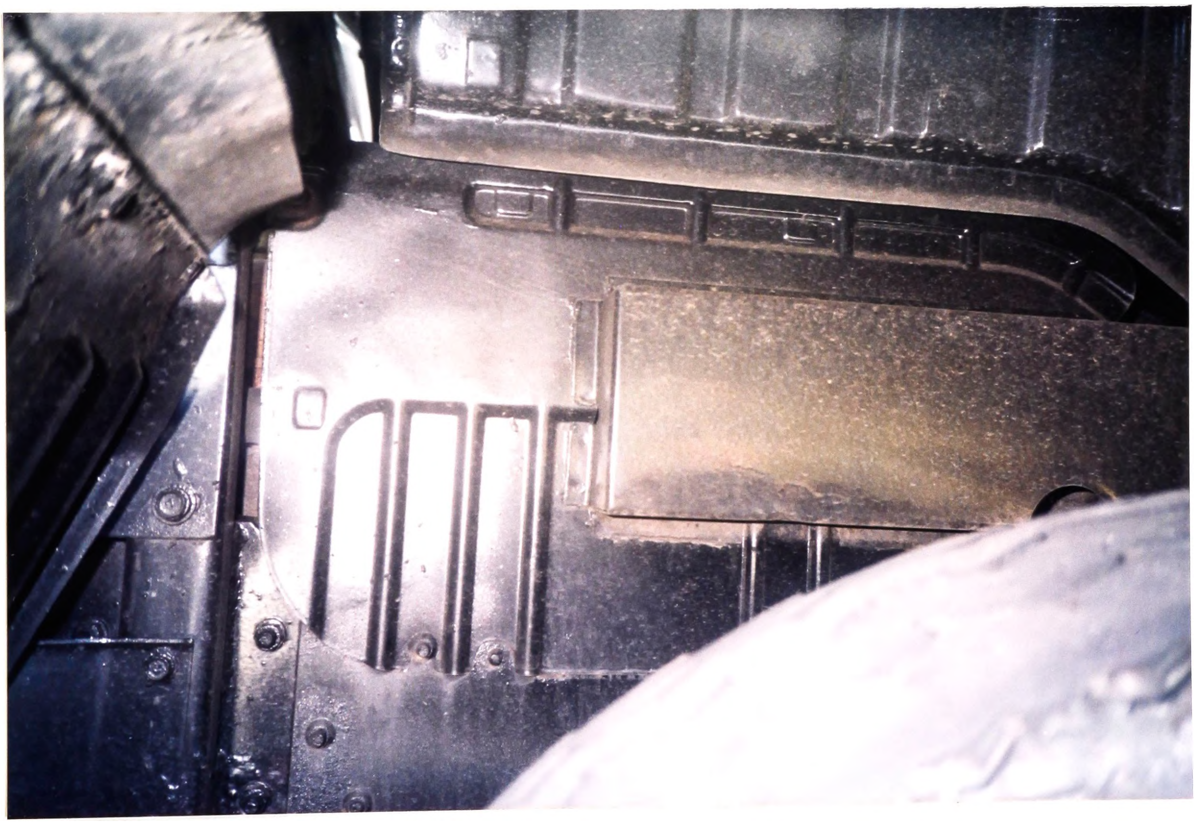


Sides of the engine

Underneath the engine sump



Gear box and transmission



Wheel arches and mud guards

Further development of duel mufflers, splitters and branch resonators

Duel mufflers

Branch resonators and splitters

Some of the instruments used for field measurements (Noise level meter, tape recorder, and radar vehicle speed recorder are seen here)

Kustom KR 11 vehicle speed recorder indicates the speed of a truck as 90 km/h

Equipment used for the tyre noise test (FM radio receiver, noise level meter, FM stereo tape recorder are seen here)

Fm Microphone mounted in the rear wheel arch of the test vehicle is seen here

Test vehicle used for the tyre noise test (Test microphone is seen under the rear wheel arch)

Test vehicle on test run at Keira Street test site

APPENDIX 4

Calculation of Transmission Loss for the barriers investigated in this thesis:

Equation 3.20 (Turner and Pretlove, 1991) for Transmission Loss was used for the calculation.

$$TL = 20 \log_{10} (\text{density X thickness}) + 20 \log10_{10} f - 42$$

Where

TL = Transmission Loss

Mass (M) = Density X Thickness

The Transmission Loss for varying frequencies ranging from 125 Hz upto 4000 hz was calculated, and the average of them was found.

Calculation: (a) For the Timber Pailing Type (Type "A") barrier:

Thickness of timber planks = 50 mm

Height of barrier = 2.1 m

Density of wood = 18 kg/m^3

Mass = Density X Thickness

Table : Transmission Loss for Type "A" Barrier

f (Hz)	20 $\log_{10}M$	20 $\log10_{10}$ f	- 42	$TL_{(spectrum)}$	$TL_{(Average)}$
125	- 0.91	41.9	- 42	- 0.81	
250	- 0.91	47.9	- 42	4.99	
500	- 0.91	53.97	- 42	11.06	14.09
1000	- 0.91	60.00	- 42	17.09	
2000	- 0.91	66.02	- 42	23.11	
4000	- 0.91	72.04	- 42	29.13	

Legend: f = frequency

Calculation: (b) For the Earth Mound Type (Type "B") barrier:

Thickness of earth mound = (2 + 5)/2

= 3.5 m

Height of barrier = 3 m

Density of earth material = 22 kN/m^3

= 22 X 10^3/9.81 kg/m^3

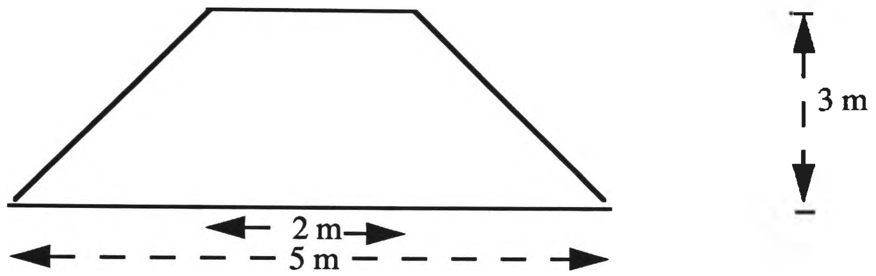
Mass = Density X Thickness

Table : Transmission Loss for Type "B" Barrier

f (Hz)	20 $\log_{10}$ M	20 $\log10_{10}$ f	- 42	TL(spectrum)	$TL_{(Average)}$
125	77	41.9	- 42	76.9	
250	77	47.9	- 42	82.9	
500	77	53.97	- 42	88.9	91.58
1000	77	60.00	- 42	95.0	
2000	77	66.02	- 42	101.0	
4000	77	72.04	- 42	107.04	

Legend: f = frequency

Barrier Type "B" Earth Mound Type



Calculation: (c) For the Corrugated Asbestos Type (Type "C") barrier:

Thickness of asbestos sheet = 4 mm
Height of barrier = 1.5 m
Density of earth material =1800 kg/m^3
Mass = Density X Thickness
= 1800 X 0.25 X 10^{-3}
= 7.2 kg/m^2

Table : Transmission Loss for Type "C" Barrier

f (Hz)	20 $\log_{10}$ M	20 $\log10_{10}$ f	- 42	TL(spectrum)	$TL_{(Average)}$
125	17.14	41.9	- 42	17.04	
250	17.14	47.9	- 42	23.04	
500	17.14	53.97	- 42	29.11	23.11
1000	17.14	60.00	- 42	35.14	
2000	17.14	66.02	- 42	41.16	
4000	17.14	72.04	- 42	47.18	

Legend: f = frequency

Calculation: (d) For the Zincalume Steel Type (Type "D") barrier:

Thickness of sheet = 0.75 mm

Height of barrier = 2 m

Mass = 8.51 kg/m^2

Table : Transmission Loss for Type "D" Barrier

f (Hz)	20 $\log_{10}$M	20 log10$_{10}$ f	- 42	TL(spectrum)	TL(Average)
125	18.59	41.9	- 42	18.49	
250	18.59	47.9	- 42	24.49	
500	18.59	53.97	- 42	30.56	33.56
1000	18.59	60.00	- 42	36.59	
2000	18.59	66.02	- 42	42.61	
4000	18.59	72.04	- 42	48.63	

Legend: f = frequency

Calculation: (e) For the Clay Brick Type (Type "E") barrier:

Thickness of wall = 25 cm

Height of barrier = 1.2 m

Density of earth material = 23.6 X 10^3/9.81 kg/m^3

Mass = Density X Thickness

= 23.6 X 10^3/9.81 X 0.25 kg/m^2

Table : Transmission Loss for Type "E" Barrier

f (Hz)	20 $\log_{10}$M	20 log10$_{10}$ f	- 42	TL(spectrum)	TL(Average)
125	55.58	41.9	- 42	55.48	
250	55.58	47.9	- 42	61.48	
500	55.58	53.97	- 42	67.59	70.5
1000	55.58	60.00	- 42	73.58	
2000	55.58	66.02	- 42	79.60	
4000	55.58	72.04	- 42	85.62	

Legend: f = frequency

As per Figure 3.11 of this thesis, the final attenuation possible due to height of each the barrier under consideration was calculated separately (where $\theta = 90^0$).

Acoordingly:

The calculation for Type "A" barrier: (where H = 2.1 m)

Frequency (Hz)	Wave Length (λ)	H/λ	Attenuation (dB)	Overall Attenuation (dB)
125	2.72	0.77	13.5	
250	1.36	1.54	16.6	
500	0.68	3.08	19.0	32.3
1000	0.34	6.17	22.0	
2000	0.17	12.35	25.5	
4000	0.085	24.70	30.0	

Overall attenuation was found by using the nomogram method as described in Section 3.6.

The calculation for Type "B" barrier: (where H = 3.0 m)

Frequency (Hz)	Wave Length (λ)	H/λ	Attenuation (dB)	Overall Attenuation (dB)
125	2.72	1.10	15	
250	1.36	2.20	19	
500	0.68	4.41	22	35.8
1000	0.34	8.82	23	
2000	0.17	2.56	18	
4000	0.085	35.2	36	

Overall attenuation was found by using the nomogram method as described in Section 3.6.

The calculation for Type "C" barrier: (where H = 1.2 m)

Frequency (Hz)	Wave Length (λ)	H/λ	Attenuation (dB)	Overall Attenuation (dB)
125	2.72	0.44	11	
250	1.36	0.88	14	
500	0.68	1.64	17	28.5
1000	0.34	3.52	19	
2000	0.17	7.05	23	
4000	0.085	14.11	26	

Overall attenuation was found by using the nomogram method as described in Section 3.6.

The calculation for Type "D" barrier: (where H = 2.0 m)

Frequency (Hz)	Wave Length (λ)	H/λ	Attenuation (dB)	Overall Attenuation (dB)
125	2.72	0.73	15.5	
250	1.36	1.47	16.5	
500	0.68	2.94	19.0	32.2
1000	0.34	5.88	23.0	
2000	0.17	11.76	26.5	
4000	0.085	23.5	29.5	

Overall attenuation was found by using the nomogram method as described in Section 3.6.

Acoordingly, the calculation for Type "E" barrier: (where H = 1.5 m)

Frequency (Hz)	Wave Length (λ)	H/λ	Attenuation (dB)	Overall Attenuation (dB)
125	2.72	0.55	12	
250	1.36	1.10	15	
500	0.68	2.20	18	29.0
1000	0.34	4.41	20	
2000	0.17	8.82	22	
4000	0.085	17.64	26	

Overall attenuation was found by using the nomogram method as described in Section 3.6.